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COMPUTER MODELS

USED BY AFGWC AND NMC FOR WEATHER ANALYSIS AND FORECASTING

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by

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13. Abstract: Describes the numerical analysis and forecast models most widely used by U.S. Air Force meteorologists. These models are: the Air Force Global Weather Central (AFGWC) Global Spectral Model (GSM); the AFGWC Real-Time Nephanalysis (RTNEPH); the AFGWC High Resolution Analysis (HIRAS) model; the AFGWC Five-Layer cloud forecast model (5-LAYER); the National Meteorological Center (NMC) Nested Grid Model (NGM); and the NMC Aviation/Medium Range Forecast (AVN/MRF) model. Report also describes model grids and tells how the grids are built. Strengths and weaknesses of the various models are discussed, along with AFGWC and NMC production cycles.

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PREFACE

Although there is a significant amount of reference material available for the computer models used by Air Force weather forecasters, there is no single reference to all the models. This technical note provides that reference by listing, describing, and comparing the computer models used by AFGWC and NMC.

Because of the complexity of atmospheric processes, numerical analysis and forecast models use approximations based on theoretical knowledge, operational considerations, and available computer power. The strengths and weaknesses of the various models depend on the type of model and the extent of the approximations that are used. Weather forecasters should understand these strengths and weaknesses, which for most models are by now well documented.

This technical note provides Air Force forecasters and others with basic descriptions of the most widely used analysis and forecast models. It is more of an operational guide than a comprehensive models textbook. We have not included the mathematical equations around which the models are built, but have tried to provide answers to such questions as, "What is a model?", "How do models work?", "What are the strengths and weaknesses of the models used?", and "Which ones apply to me?".

Interested readers should also see the following: AFGWC/87-001, *AFGWC Cloud Forecast Models*; AFGWC/88-001, *The AFGWC Automated Real-Time Cloud Analysis Model*, AWS/86-001, *AFGWC's Advanced Weather Analysis and Prediction System (AWAPS)*; and AFGWC/79-004, *The AFGWC Automated Analysis/Forecast Model System.*

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Chapter 1

WHAT IS A COMPUTER MODEL?

1.1 The Model Explained. An atmospheric computer model is a set of mathematical equations that describe the movement of the atmosphere and present a graphic view of current and forecast atmospheric conditions. The first successful run of such a model took place in 1950 at Princeton University, where it took 24 hours to make a 24-hour forecast. Model forecasts are not perfect for the following reasons:

- We have an incomplete understanding of the atmosphere.

- Scientists have not been able to describe all atmospheric processes mathematically.

- The mathematical equations that describe atmospheric motions do not provide exact solutions; they must be approximated.

- Observations are geographically scattered; in some areas, they are nonexistent. Because information for data-sparse areas must be interpolated from surrounding gridpoints, there can be errors in gridpoint data.

- Computer memory size and central processing unit (CPU) speed are limited. As a result, only a limited range of atmospheric features can be predicted. The smallest feature the Air Weather Service Primitive Equation (AWSPE) model (no longer in use) could forecast with its 381-km grid mesh was 1,524 sq km, or an area about the size of the Midwest.

1.2 Improving the Model. Computer models can be improved, but to do so is expensive and time-consuming. For example, while forecast accuracy can be improved 10-15% by halving the grid space, it would take four times as long to run such a model on the same computer. The time step (the time it takes for the fastest model wave to move from one gridpoint to another) would have to be halved, increasing the CPU requirement by a factor of two. The combined result would be an increase by a factor of *eight*; that is, if the AFGWC Global Spectral Model (GSM) took 20 minutes to run normally, it would take 160 minutes to run at two times the resolution on the same computer. This alone makes increasing the grid resolution by two an ineffective way to increase forecast skill.

1.3 Problems. The major problems with numerical weather prediction are:

1.3.1 Physics (about 30%). Physics problems stem from our lack of a complete understanding of the atmosphere and the resultant need to *approximate* some processes because computer size and speed are limited. For example, turbulence and friction are *parameterized,* meaning that the calculation of subgrid scale processes (those processes that are too small to be detected on the grid) are approximated on a grid-scale basis.

1.3.2 Initial conditions (about 25%) are the most difficult to correct. They are problematic because:

• Weather observing stations are located at random, rather than at the exact gridpoints of the model. Observations are concentrated in some areas, such as the United States and Europe, and sparse in others, such as Asia.

• Weather observations often contain errors.

• Weather observations are often inconsistent, partly because of the methods used to collect the data and partly because of calculation errors (for example, RAOB and satellite temperatures for the same point may be different).

1.3.3 Resolution (about 40%). In a grid model, the smallest wave that can be seen or resolved horizontally is *two grid lengths*; that is, if the grid space were 200 km, the smallest resolvable wave would be 400 km long.

Aliasing. During the forecast process, false waves that are four or less grid lengths long are created by the mathematical terms within the model. These false waves, if not removed, will cause the model to become unstable.

Time Step. The time step in a model must be smaller than a certain value or the model will become unstable and produce meaningless results.

Phase Speed. Gridpoints in most numerical models are fixed, both horizontally and vertically. Because of this, small perturbations occurring during the forecast process tend to move more slowly than they would in reality.

Spectral vs. Gridpoint Models.

Gridpoint models use U-V wind components to represent the vector value of the wind at each individual gridpoint. Wind is a vector that includes both speed and direction. Wind vectors can be resolved into eastward (U) and northward (V) components. Analysis and forecast models resolve wind vectors into west-to-east (+U) and south-to-north (+V) components.

Spectral models use sine and cosine functions to represent weather elements such as wind and temperature. These sine and cosine functions go through changes in amplitude during the forecast process. Because of this special characteristic, spectral models do not have the aliasing and phase speed problems mentioned above.

Chapter 2

GRIDS

2.1 AFGWC Grids. For our purposes, the only grid types discussed (unless otherwise specified) are those in use at AFGWC.

2.2 Grids Basic to Models. The starting point for any gridpoint-based model is the grid. The atmosphere is relatively shallow in the vertical, but broad horizontally. This is why the number of gridpoints in the horizontal is usually greater than the number of gridpoints in the vertical. In the horizontal, the gridpoints are equally spaced. In the vertical, points are "stacked" to represent those areas of the atmosphere that are commonly analyzed or that are of significance to the model (e.g., 850 mb, 700 mb, 500 mb). Grid spacings and vertical stacking are chosen in such a way as to simplify the calculations of the forecast model and to provide outputs tailored for a specific customer's use.

2.3 The Grid Described. A grid is a group of regularly spaced points that represent the intersection of regularly spaced parallel and perpendicular lines--see Figures 1 and 2. The standard and lowest resolution grid used at AFGWC is the whole mesh. Higher-resolution grids (or finer-mesh grids) use whole-mesh gridpoints as a starting point and have more gridpoints in the horizontal. For example, the half-mesh grid is simply a grid that contains the whole mesh gridpoints and one gridpoint between every whole mesh gridpoint. Figure 3 is an example of the relationship between whole-mesh, half-mesh, and quarter-mesh gridpoints.

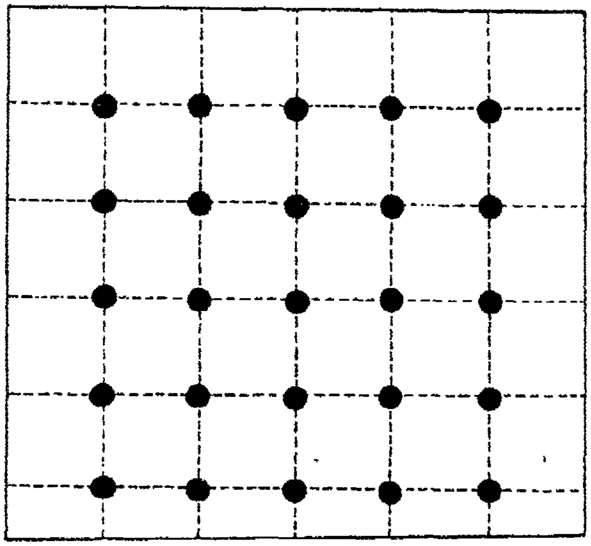

Figure 1. An Example of a Grid. A grid is simply an array of points located at the intersections of uniformly spaced parallel and perpendicular lines (from Hoke et al., 1985).

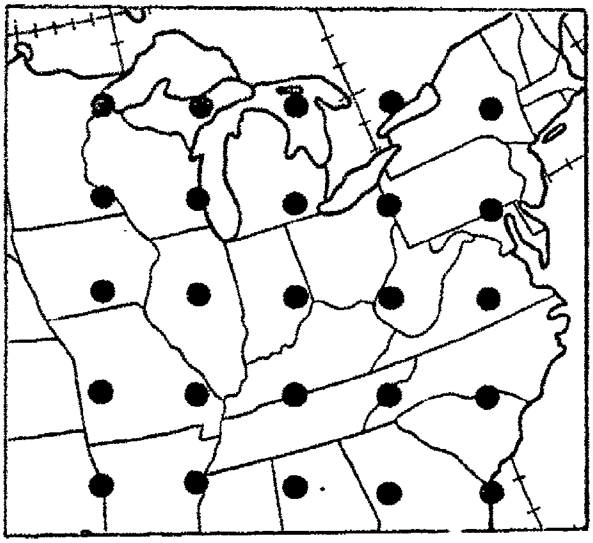

Figure 2. An Example of a Grid Superimposed on a Map. (From Hoke et al., 1985).

2.4 Grid Resolution. Atmospheric motions on a scale smaller than the grid in use cannot be represented correctly because wavelengths must be equal to or greater than twice the distance between two adjacent gridpoints. Also, a wave is generally handled poorly if its wavelength is less than four gridpoints wide. Since many atmospheric events deal with motions smaller than 1,600 km--the distance covered by four successive whole-mesh gridpoints--grids with finer resolution were developed. These include the half-mesh, quarter-mesh, eighth-mesh, and sixty-fourth-mesh grids. As their names imply, the distance between gridpoints on the finer meshes is defined relative to the whole-mesh.

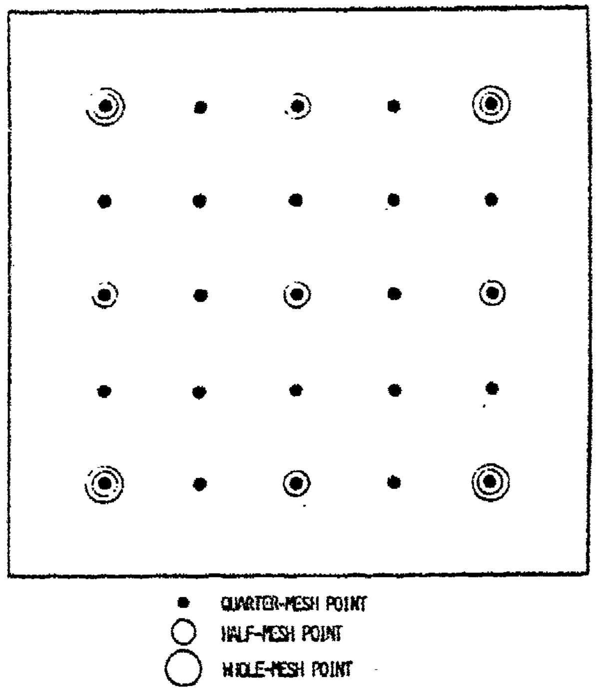

Figure 3. The Relationship Between Whole-Mesh, Half-Mesh, and Quarter-Mesh Gridpoints. Note that each whole-mesh point is a half-mesh and quarter-mesh point, as well. Similarly, each half-mesh point is also a quarter-mesh point (from Hoke et al., 1985).

2.5 The Whole-Mesh Grid. Whole-mesh gridpoints are exactly 381 km apart at 60° N relative to the Earth's surface. This means that, because of the Earth's curvature, resolution decreases toward the poles and increases toward the Equator. At half-mesh, the gridpoints are 190.5 km apart. Higher resolution grids have successively smaller distances between gridpoints. An example of the whole-mesh grid is shown in Figure 4.

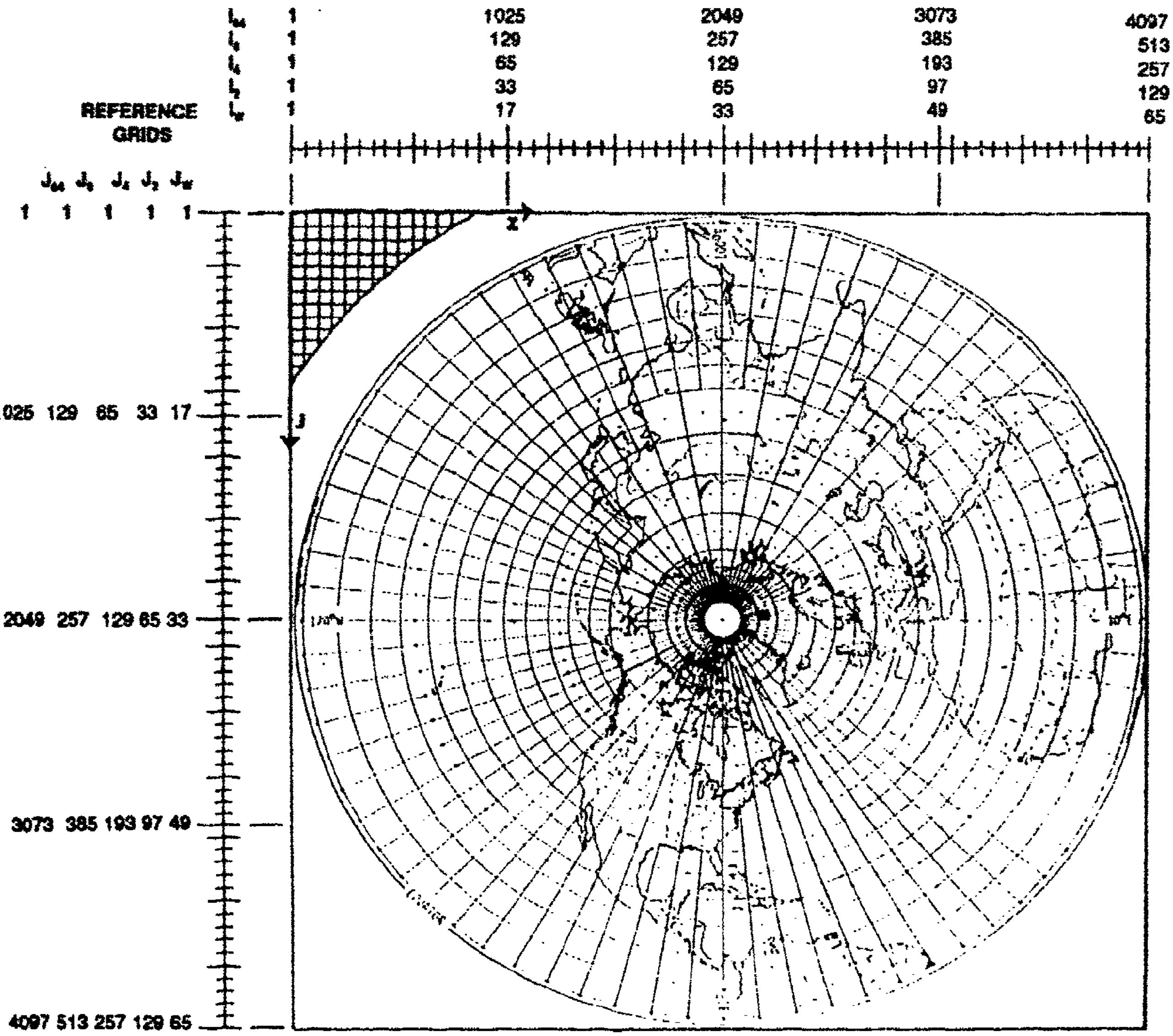

Figure 4. The Northern Hemisphere Whole-Mesh Grid. The grid spacing is displayed in the upper left-hand corner. Note that the grid extends beyond the boundaries of this map. The I,J indexing convention is also displayed. This convention allows for I,J labeling of every gridpoint. I_w and J_w coordinates represent the whole-mesh grid scale. I_2 and J_2 represent the half-mesh grid, and so on (from Hoke, et al., 1985).

2.6 Hemispheric Data Displays. The following are two examples of gridded hemispheric data displays (CRT and paper facsimiles):

- The first uses all whole-mesh-based gridded data from the poles to the Equator. Gridpoints beyond the Equator are ignored.

- The second is the octagon, shown in Figure 5. An example of gridded data in an octagonal display is the Cloud-Free information on AFGWC Horizontal Weather Depiction (HWD) products. Data in this display extends from the pole to the borders of the octagon. All data beyond the octagon's borders is ignored. Limitations of gridded data displays are generally based on computer processing capabilities and the printing equipment available at the time the model was designed.

2.7 Stationary Window Grids use windows, or subsets of the whole-mesh grid, to cover specific areas of the globe such as the North American, European, and Asian continents.

2.8 The Satellite Global Database (SGDB) Grid. This 64th-mesh grid contains 16,777,216 points in the Northern Hemisphere. It is used in the SGDB display on the Satellite Data Handling System (SDHS), with a resolution of about 5 km.

2.9 Grid Types. There are three grid types in use at AFGWC: *polar stereographic, Mercator,* and *latitude-longttude.*

Polar-stereographic (PST) Grids. The Northern (or Southern) Hemispheric Whole-mesh Reference Grid (sometimes called the "Northern Hemispheric Whole-Mesh Super Grid") is a 65 X 65 point whole-mesh grid based on the PST map--see Figure 5. The domain for all PST grids are centered on the hemisphere (Northern or Southern) and include the entire hemisphere. The borders of the grids partially extend into the opposite hemisphere, but data in these overlap areas are usually ignored. PST grids are available in the half-, quarter-, eighth, and 64th-mesh resolutions. They are used extensively at AFGWC for various weather support functions.

Mercator Grids. These grids cover an area from 50° N to 50° S for tropical meteorological needs. They are based on the mercator map projection.

- *The Conventional Tropical Grid* is used for conventional meteorological elements such as temperature, height, and wind--see Figure 6.

- *The Satellite Global Database Tropical Grid* is used for procssing satellite imagery; see Figure 7.

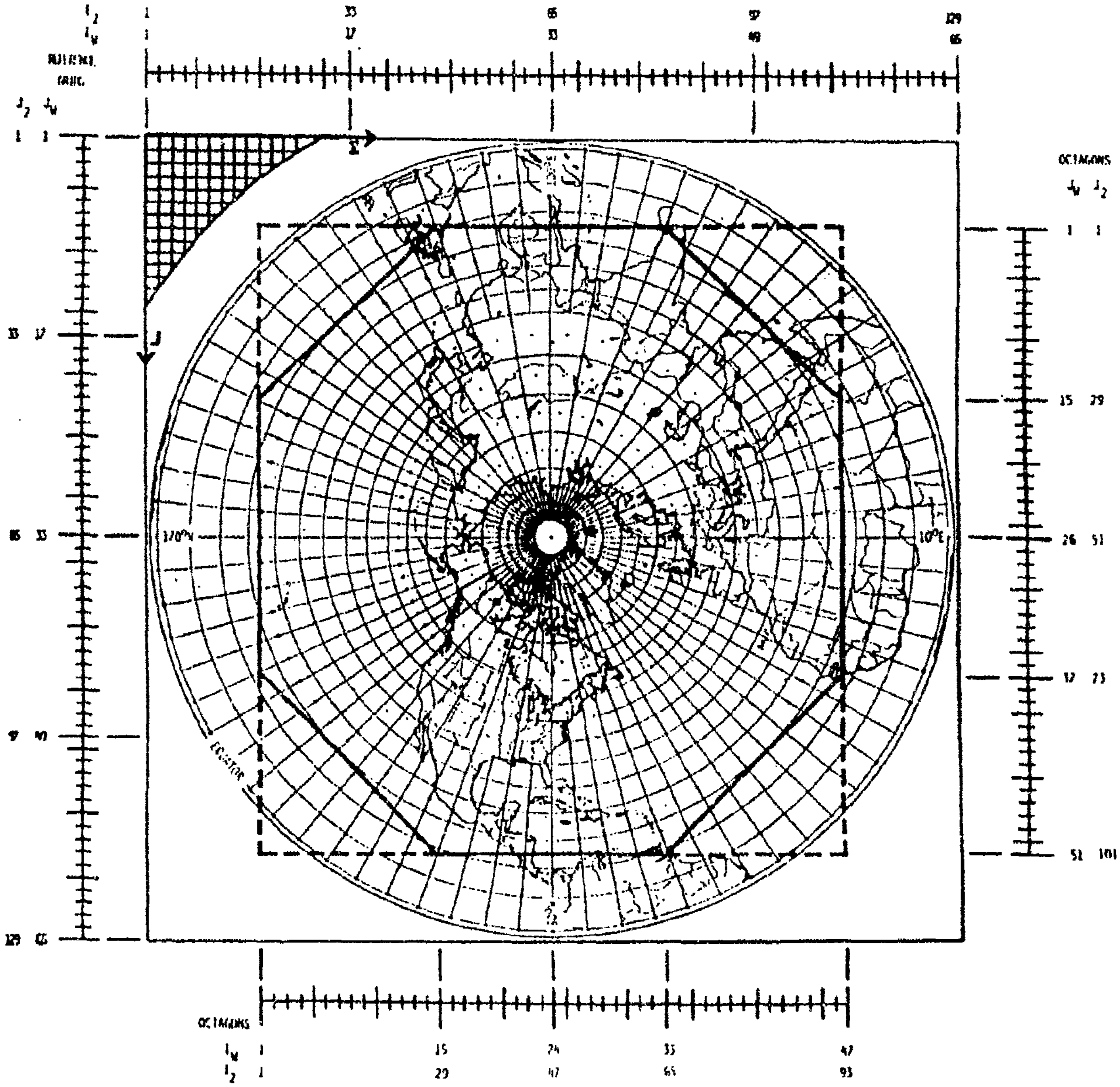

Figure 5. An Example of a Polar-Stereographic (PST) Grid (Whole-Mesh) with the Octagon Grid Boundaries Centered on the Northern Hemisphere. The dashed lines indicate that the data on the octagon grid is actually stored in a rectangular database. All data in the corners of the rectangle (outside the octagon) are ignored. The reference grid for the octagon is the outer whole-mesh grid (from Hoke et al., 1985).

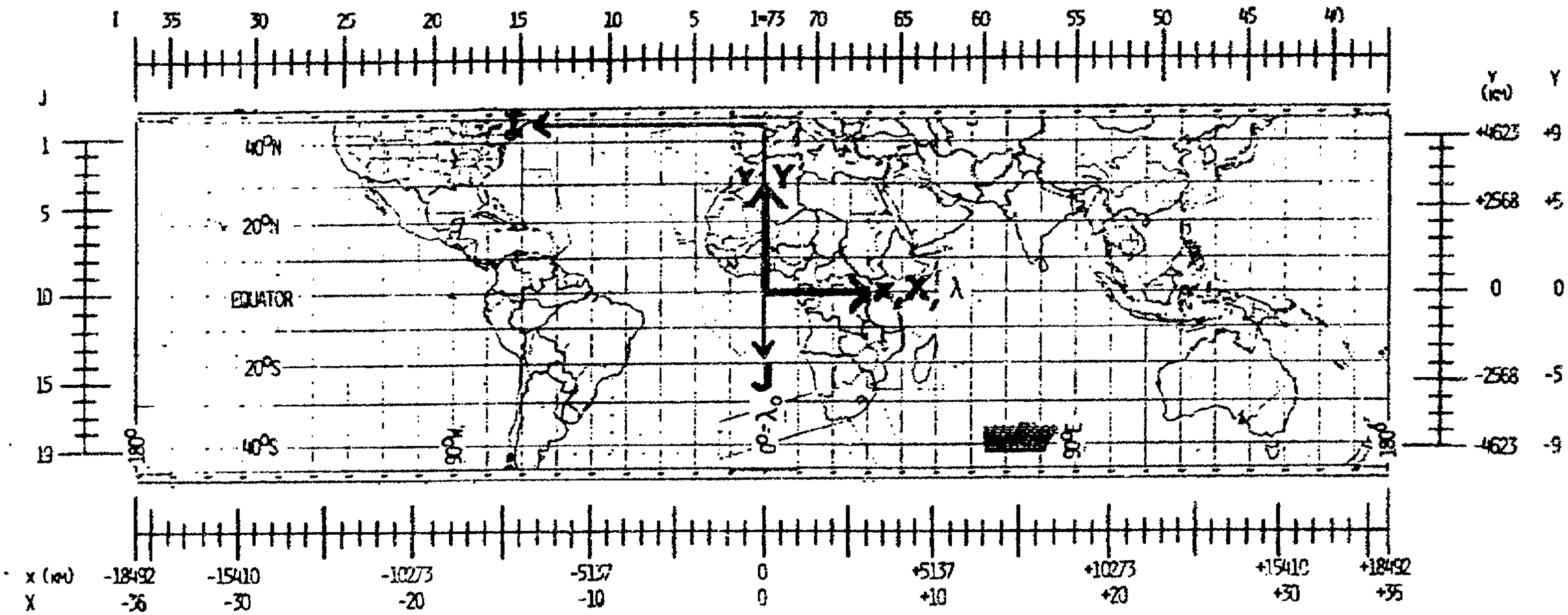

Figure 6. The Conventional Tropical Grid is an Example of a Mercator Grid.

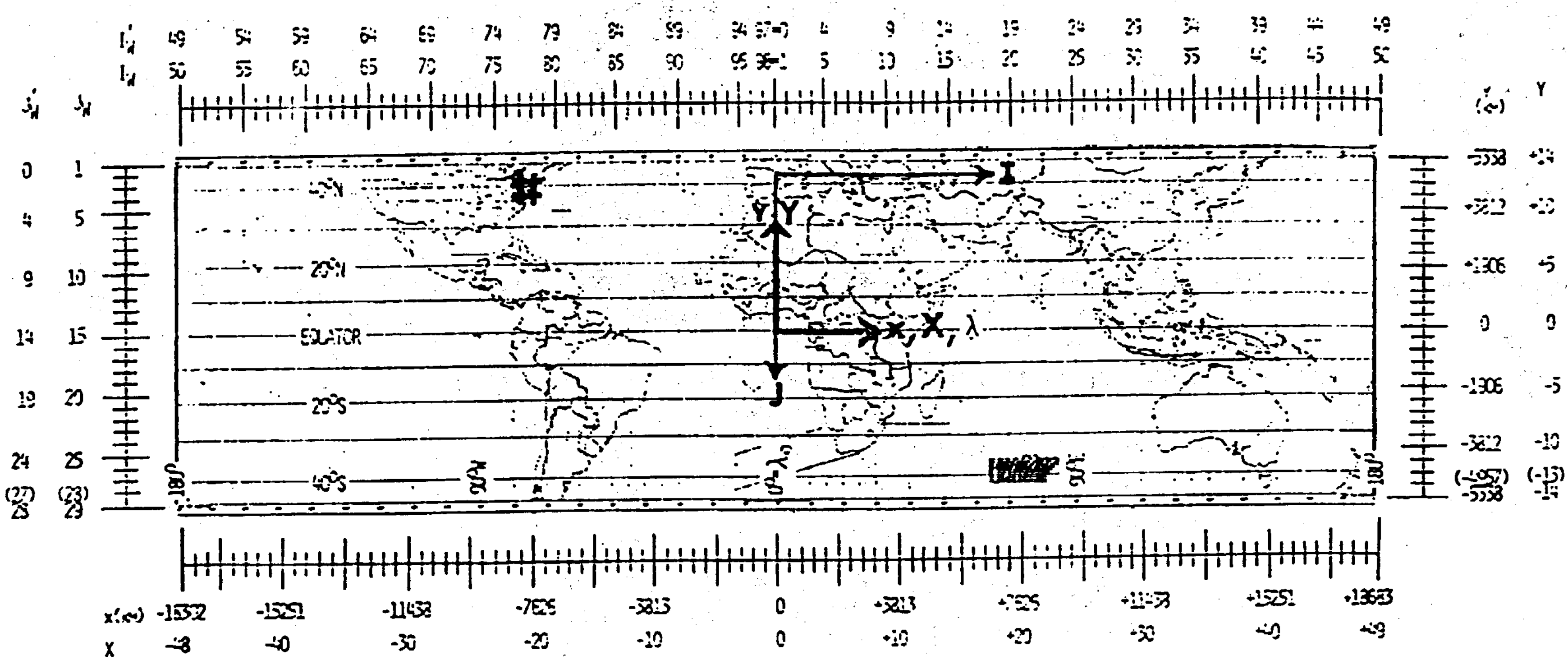

Figure 7. The Satellite Global Database Tropical Grid. This grid is similar to the one in Figure 6, but it is used for processing satelite imagery.

Latitude-Longitude Grids. The Global Applications Database (GADB) grid and the High Resolution Analysis System (HIRAS) grid are the latitude-longitude grids in use at AFGWC; an example is shown in Figure 8. Grid spacing on both is 2.5° x 2.5°. Both contain 10,585 points.

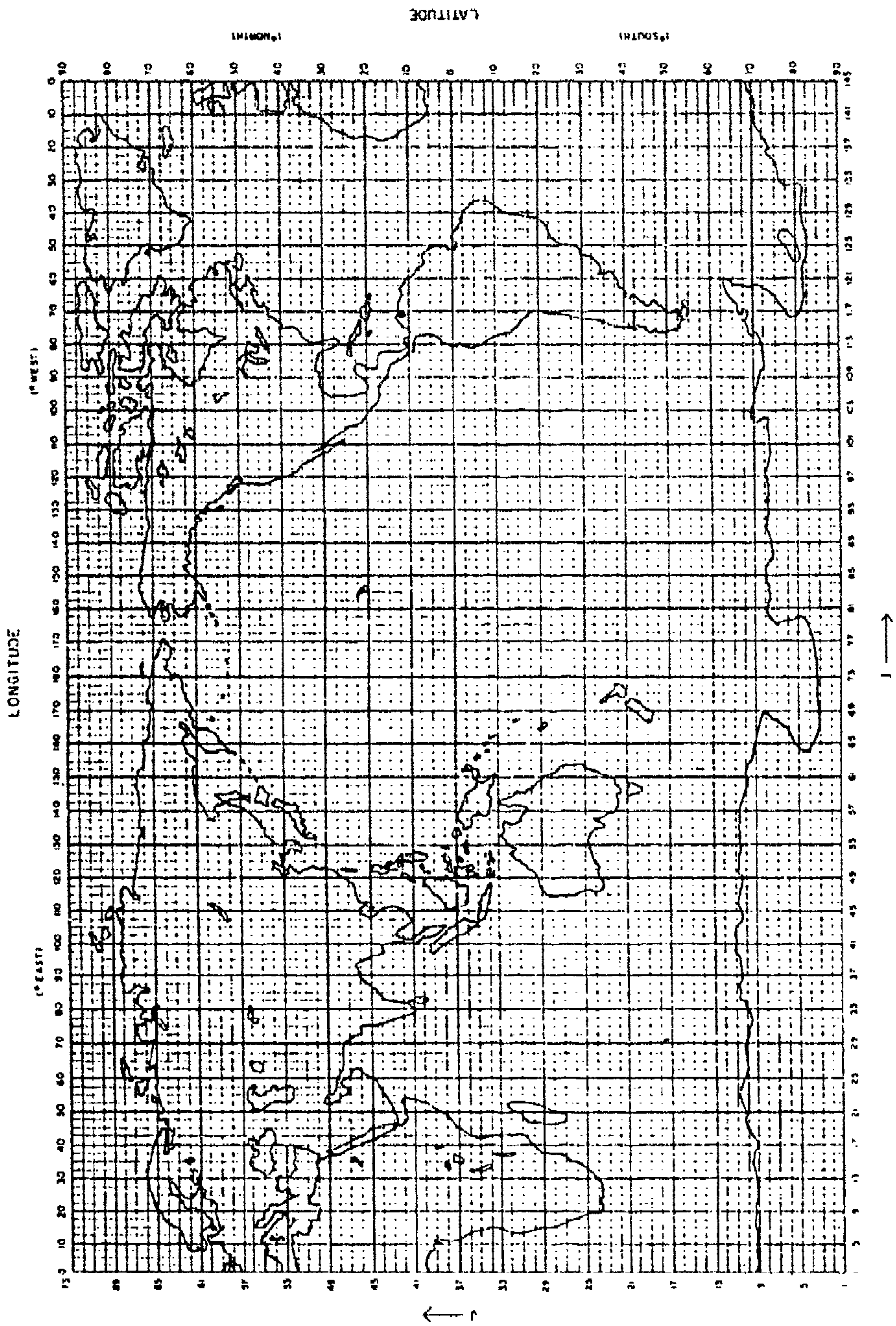

Figure 8. An Example of the Latitude-Longitude Grid. This is the grid on which HIRAS stores its output (from Hoke et al., 1985).

Chapter 3

THE AFGWC PRODUCTION CYCLE

3.1 The Advanced Weather Analysis and Prediction System (AWAPS) was installed at AFGWC in 1985, and formally implemented in June 1986. It produces nearly all of AFGWC's automated forecasts except for clouds. AWAPS comprises four models: the Global Spectral Model (GSM), the First-Guess model, the High Resolution Analysis System (HIRAS) model, and the Relocatable Window Model (RWM). Figure 9 shows how the GSM and HIRAS processing cycles are linked to form part of the AFGWC production cycle, a series of forecasts, analyses, and reanalyses that runs at 6-hour intervals.

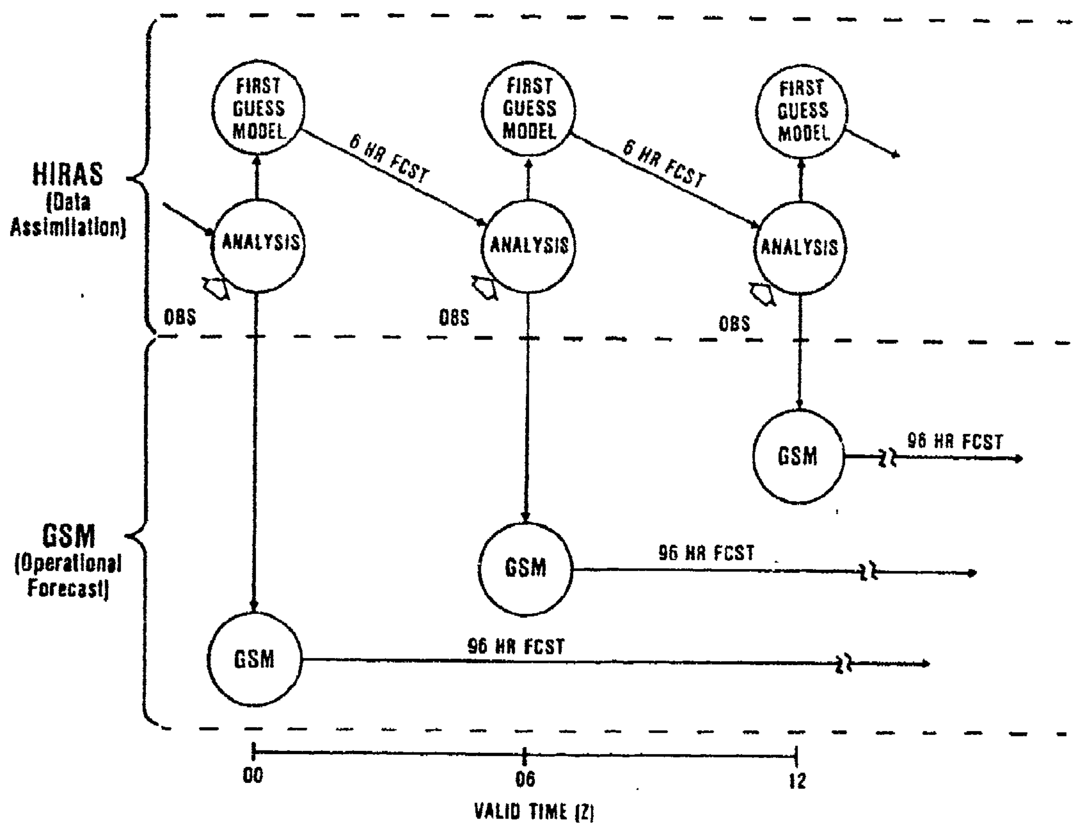

Figure 9. The HIRAS/GSM Relationship in the AWAPS Production Cycle (from Hoke et al., 1985).

3.2 The AWAPS Cycle. Both the GSM and First-Guess are updated every 6 hours; although slightly different, they provide similar product support. The HIRAS uses the First-Guess data fields to produce the best possible initial analysis for the next 6-hour cycle. The 0000Z cycle is shown below as an example:

At 0100Z, the First-Guess is ready for quality control (QC) by forecasters. "Bogus" data (this will be explained in a later chapter) can be input to alter the First-Guess data fields and improve the analysis.

At 0130Z, the HIRAS surface analysis is run. It takes 10 minutes to run the surface analysis on the CRAY/X-MP mainframe computer. Satellite soundings are anchored periodically using this or one of the next three surface analyses. Satellite soundings are built by adding thickness values to the surface HIRAS 1,000 mb analysis field.

At 0230Z, the HIRAS surface analysis is run for the second time. It is also used to anchor the satellite soundings for the first upper-air analysis.

At 0300Z, the HIRAS upper-air analysis is run on the CRAY/X/MP. It takes 20 minutes.

At 0400Z, the GSM is run out to 96 hours using the HIRAS first upper-air analysis for its initial conditions. It takes 1.5 hours to run the model on the CRAY/X-MP.

At 0530Z, HIRAS does its third surface analysis; it is again used to anchor satellite sounding data.

At 0600Z, a second upper-air analysis is run. 0000Z data will continue to come in up to this point; all the new data available is essential for making the best possible 0000Z analysis.

At 0630Z, the First-Guess model makes its 6-hour forecast using the second HIRAS 0000Z upper-air analysis for its inital conditions. It takes 30 minutes to run out to 12 hours on the CRAY/X-MP. When finished, the cycle begins again.

3.3 First-Guess Accuracy. In order to have a more accurate First-Guess, the model produces a forecast every 6 hours. This forecast is then used by HIRAS. A 6-hour cycle provides a higher quality analysis than would a 12-hour cycle; the analysis is updated more often and used for initializing the next forecast run, which in turn produces a better forecast.

3.4 The Relocatable Window Model (RWM) is being developed for inclusion in the AWAPS production cycle. It is designed to make a high-quality and high-resolution forecast anywhere in the world at any time.

Chapter 4

THE HIGH RESOLUTION ANALYSIS SYSTEM (HIRAS)

4.1 The HIRAS Model. HIRAS is an analysis model used primarily to initialize the forecast models. It is extremely important. HIRAS deficiencies can dramatically alter the outcome of the forecast models.

4.2 HIRAS Input Data. HIRAS uses observations from land stations, ships, buoys, aircraft, radiosondes, and satellites (see Figures 10-15 for typical global distributions of the various observation types). Although HIRAS applies most of the data available to it to its internal grid, it can't use all the data because of software and hardware limitations. The output of the First-Guess model is essential to the run of the HIRAS model. HIRAS blends its own data with the output from the First-Guess model (a 6-hour forecast valid at the same time) to create the best possible analysis.

4.3 Optimum Interpolation (OI). HIRAS does its analysis using a technique called "Optimum Interpolation," an analysis technique used by most contemporary analysis models. Our discussion of OI is based on the version used by HIRAS. Basically, there are three things OI considers:

- The number of observations available and the distance between them and the analysis grid point.

- The precision of the equipment used to take the observations.

- The statistical accuracy of the First-Guess fields.

4.3.1 Observation/Gridpoint Distance. The use of the mean distance between observations is not unique to OI; it is found in nearly every other numerical analysis scheme. In very simple terms, the model assigns weights to observations surrounding each gridpoint. Each observation is allowed to influence surrounding gridpoints by the weight it carries; weights decrease exponentially with distance. Observations in the vertical are also assigned weights. All the observations and their weights are applied mathematically to the First-Guess data at all gridpoints and atmospheric levels to modify the First-Guess data as needed.

4.3.2 Accuracy of the Observing Instrument. The model is able to distinguish between the various observing instruments used. Each instrument type is assigned a statistically determined expected error. The lower the expected error, the more weight the observation carries. For example, a 500-mb temperature from a radiosonde, which is probably more accurate than the 500-mb temperature from a satellite sounding, is assigned a higher weight.

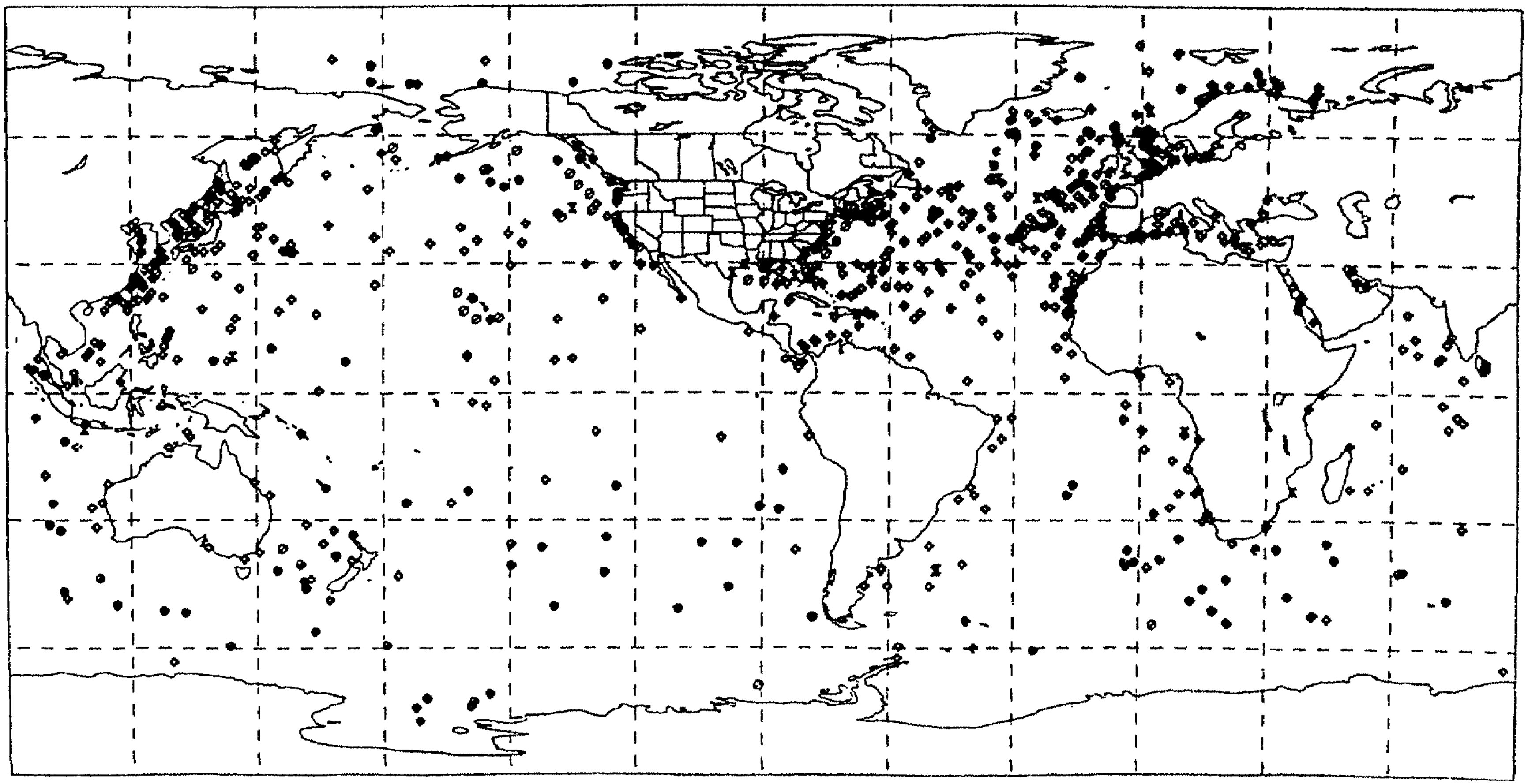

Figure 10. Typical Distribution of Surface Marine Observations at 1200Z (from Dey, 1989).

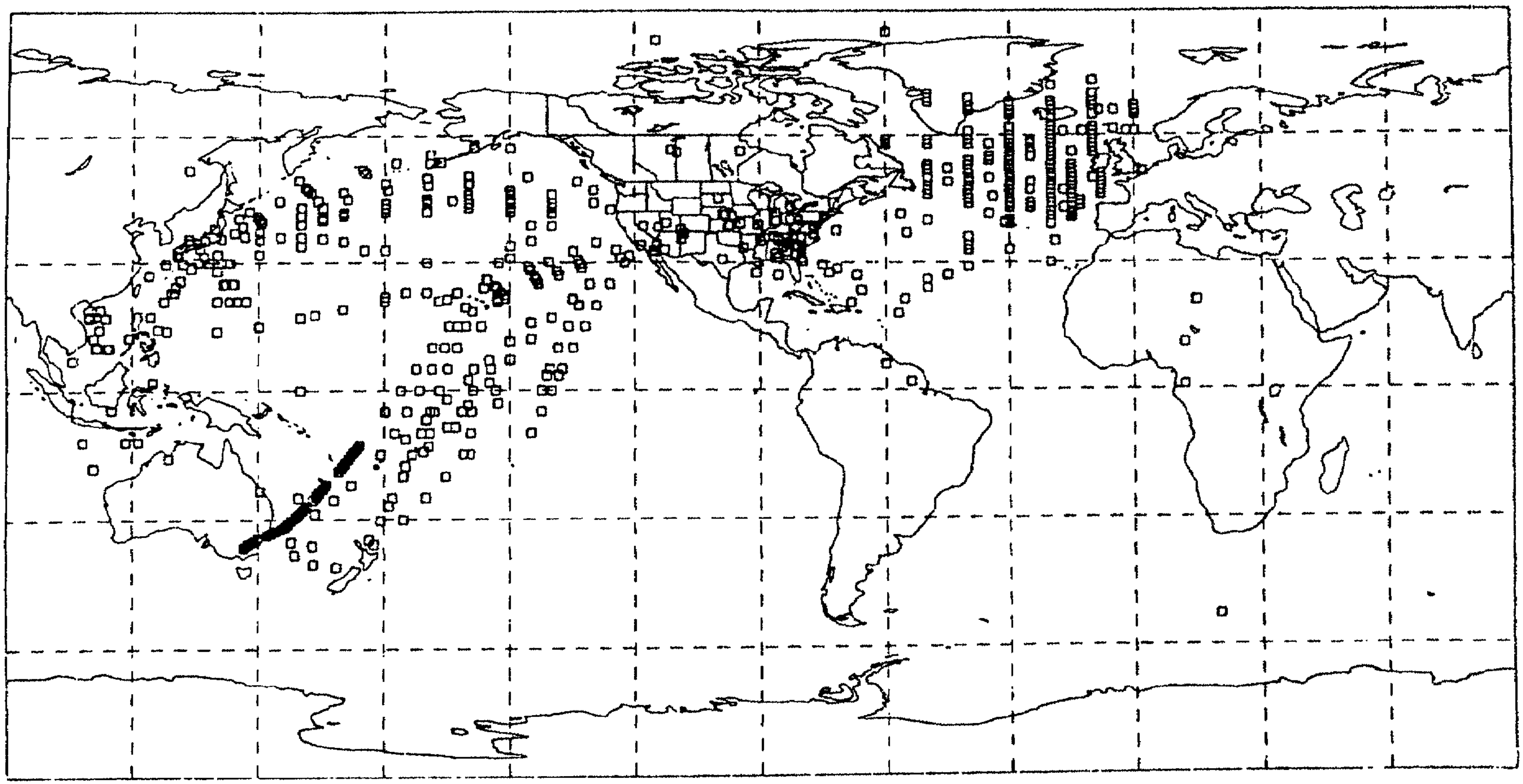

Figure 11. Typical Distribution of Aircraft and ASDAR (Aircraft to Satellite Data Relay) Observations at 1200Z (from Dey, 1989).

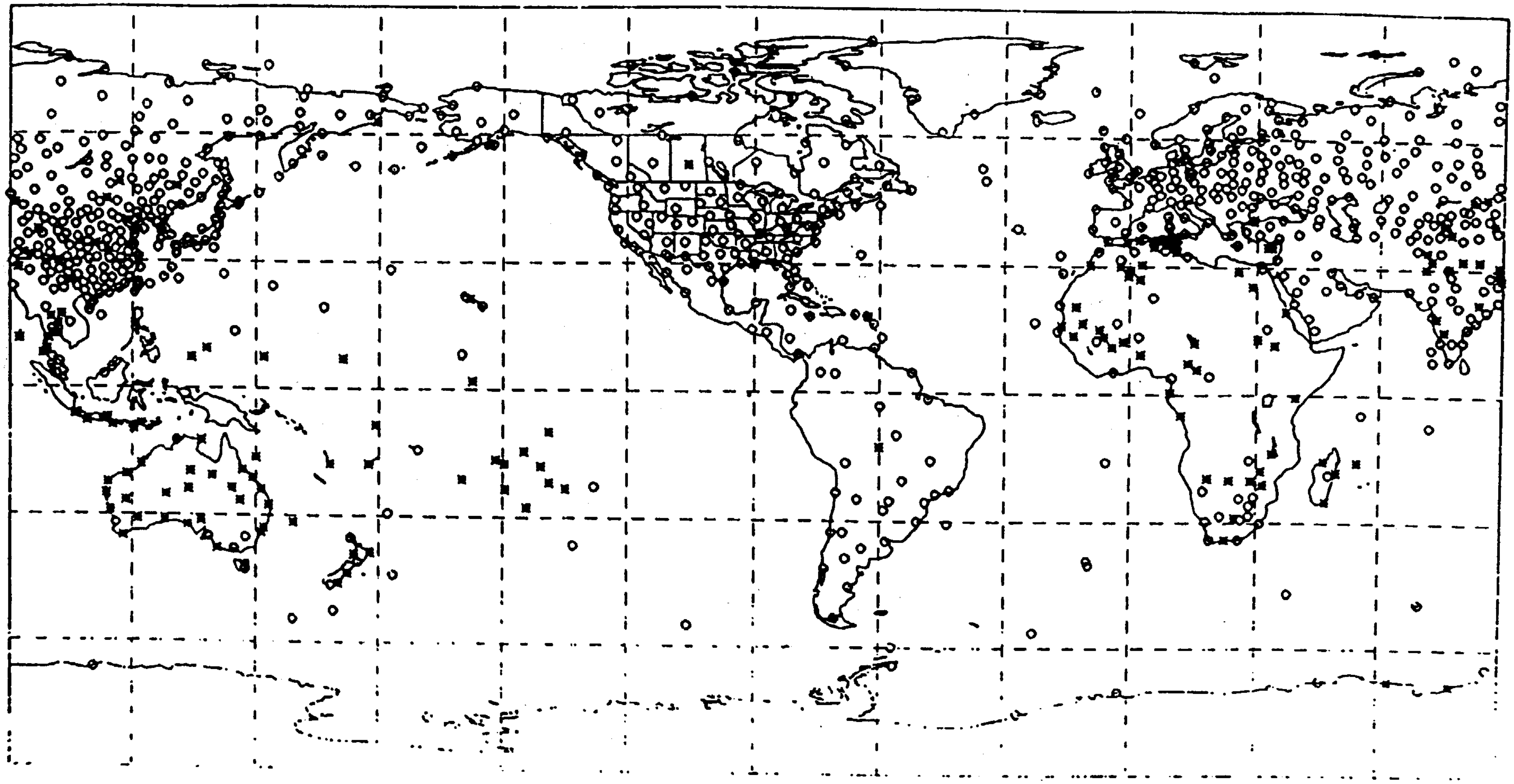

Figure 12. Typical Distribution of Upper-Air Soundings at 1200Z (from Dey, 1989).

Figure 13. Typical Distribution of Satellite Temperature Profile Soundings at 1200Z (from Dey, 1989).

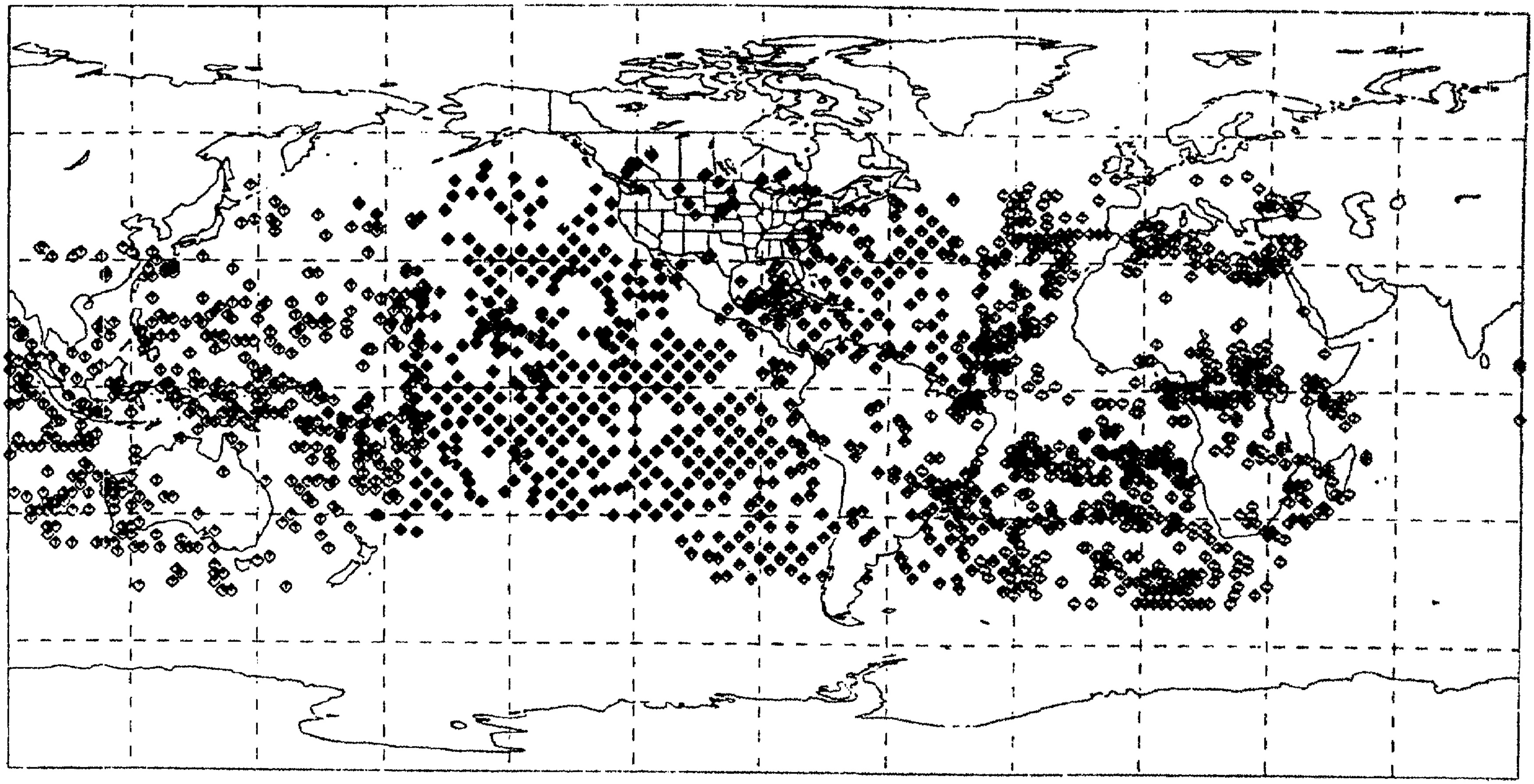

Figure 14. Typical Distribution of Cloud-Tracked Wind Observations at 1200Z (from Dey, 1989).

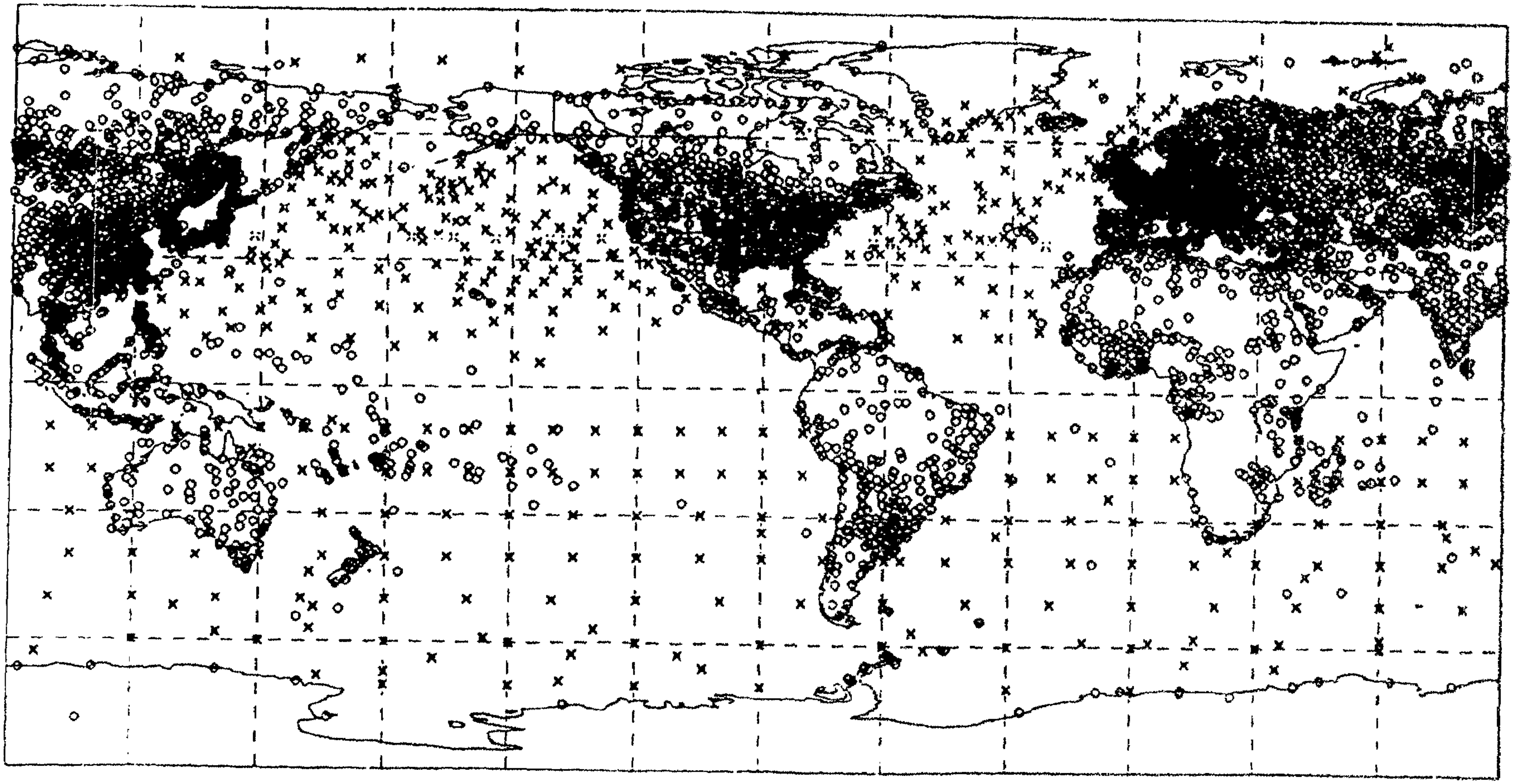

Figure 15. Typical Distribution of Land Surface and NMC Sea-Level Bogus Observations for 1200Z (from Dey, 1989).

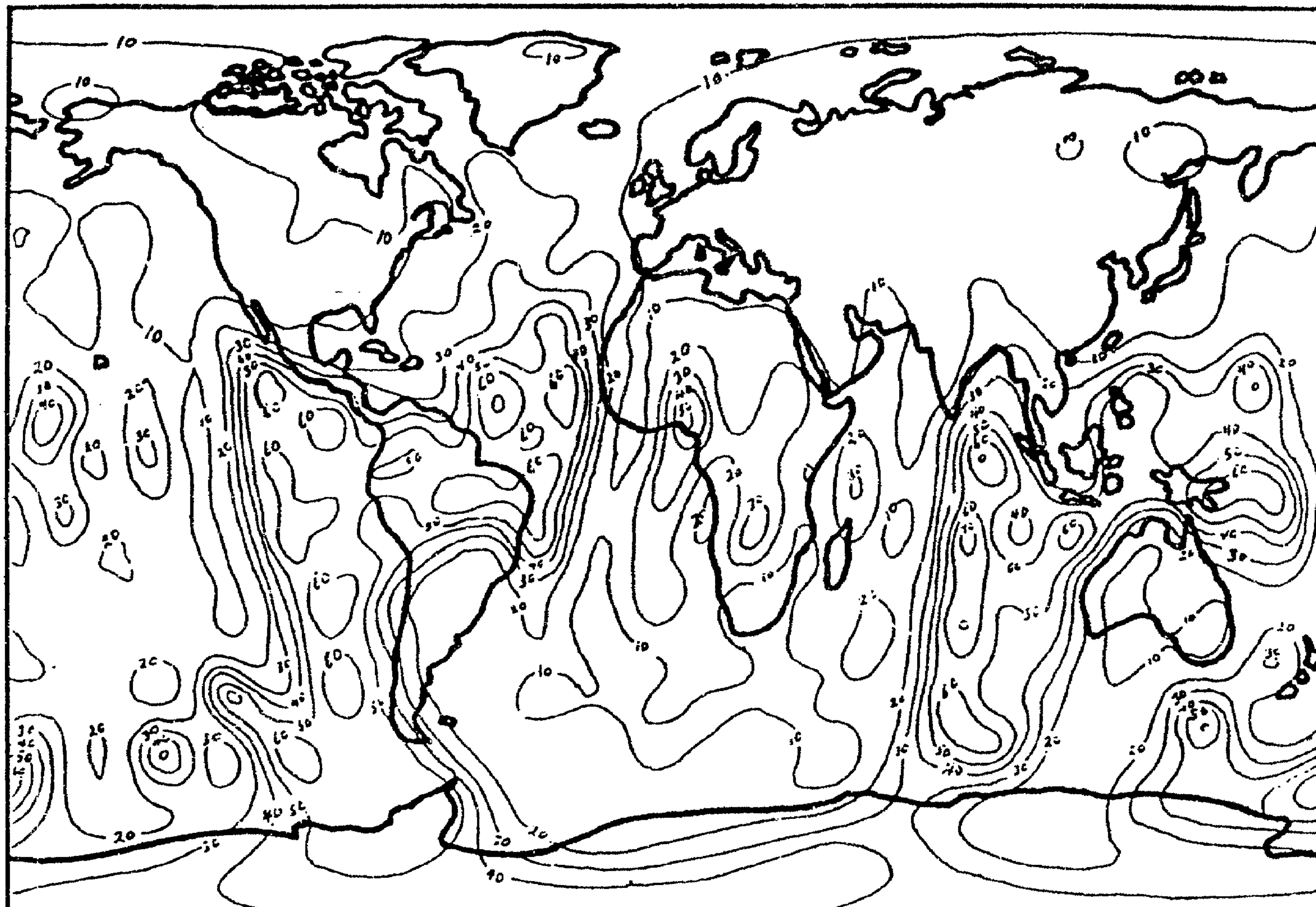

Figure 16. An Example of the 250-mb HIRAS Error Fields as Applied to the First-Guess During the Analysis Run (from Stobie, 1986).

4.3.3 First-Guess Accuracy. HIRAS produces a set of fields (called "error fields") that indicate how accurate the analyses are at all gridpoints. Essentially, the more observations there are to influence given gridpoints, the more accurate the resulting analysis will be. Figure 16 (opposite) is an example of a 250-mb height error field. Note that error values are low over data-rich areas such as North America but high over data-sparse areas such as the Indian Ocean. In addition to indicating analysis accuracy, error fields also indicate the accuracy of the First-Guess.

To see how this works, let's consider two areas, North America and the South Pacific. Since there are a large number of radiosonde stations there, the analysis over North America is considered accurate. But there are very few upper-air stations in the South Pacific; although a satellite makes an occasional pass, satellite data is not nearly as reliable as radiosonde data. As a result, initial conditions in the South Pacific are usually poorly handled by the First-Guess model and the First-Guess over the South Pacific is not usually as accurate as over North America.

Since there is this difference in First-Guess accuracy from place to place, HIRAS OI gives more weight to the First-Guess data when compared to any individual observation in data-rich areas like North America and more weight to individual observations in data-sparse areas like the South Pacific. The aggregate of observations in data-rich areas, however, usually carry more weight when applied to an individual First-Guess gridpoint. The obvious question is "Why doesn't the HIRAS always place more emphasis on observations from data-rich areas?"

OI uses a combination of observations and the First-Guess. The better the First-Guess (and it usually is better in data-rich areas) the less the weight given to individual observations. Observations also contain errors. A radiosonde, for example, might have a 3° C temperature error. If the First-Guess had an expected error of only 1° C, it wouldn't make sense to use only the RAOB. All the data available around any given gridpoint is used unless the QC function determines the data to be bad. OI determines how much each piece of data will affect the final output for a given gridpoint.

Although it doesn't happen often, HIRAS may not recognize dramatic changes in atmospheric conditions quickly. The First-Guess model has considerable weight in data-rich areas. If the observations show a dramatic difference and the First-Guess is really wrong, only a portion of the difference will be used to affect the outcome of the analysis. In rare circumstances, it may take a couple of forecast cycles for HIRAS to recognize rapid changes.

4.4 The Two HIRAS Models.

HIRAS is really two different models: upper-air and surface.

4.4.1 The Upper-Air Analysis extends from 1,000 to 10 mb and is used to initialize the GSM. HIRAS directly analyzes only five different fields: geopotential heights, U-component wind (West-East), V-component wind (South-North), temperature, and relative humidity. From these five, HIRAS derives thirteen other fields. A number of other fields not produced by HIRAS (e.g., thickness and vertical velocity) are produced on other computer processors using the HIRAS fields. Table 1 provides a list of all the fields produced by HIRAS or derived by HIRAS outputs.

TABLE 1. List of fields analyzed by or derived from the HIRAS upper-air model. Numerous other fields are processed through algorithms on SDHS. The list includes the levels/layers in millibars for which the data are available.

FIELD directly analyzed	Height/Layer in Millibars
Relative Humidity	sfc, 1000, 850, 700, 500, 400, 300
Heights	1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
Temperature	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
U-Component winds	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
V-Component wind	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
FIELDS derived	**Height/Layer in Millibars**
Temperature Advection	50
Streamline Functions	1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
Specific Humidity	sfc, 1000, 850, 700, 500, 400, 300
Tropopause Height	*
Tropopause Pressure	*
Tropopause Temperature	*
Sea Level Pressure	sfc
Dewpoint	sfc, 1000, 850, 700, 500, 400, 300
Precipitable Water	sfc-850, 850-700, 700-500, 500-400, 400-300, 300-100
Vorticity Advection	850, 500
Vorticity	850, 500, 300
**Packed U-V Winds	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
***Hours Since Land	sfc (boundary layer)

* Tropopause data varies with respect to its exact position.

** Packed U-V Winds - the individual U and V wind components contain too many bits of information and must be compacted for SDHS to use them.

*** Describes the amount of time a boundary layer parcel, currently over water, has spent over water.

The upper-air analysis, which is displayed using a 2.5° x 2.5° latitude-longitude grid, is actually run on the Kurihara grid (shown in Figure 17) to save computer time. The Kurihara grid, with a coarser (or lower) resolution, has about a third as many gridpoints as the display grid. The upper-air analysis uses a spectral transformation along with OI.

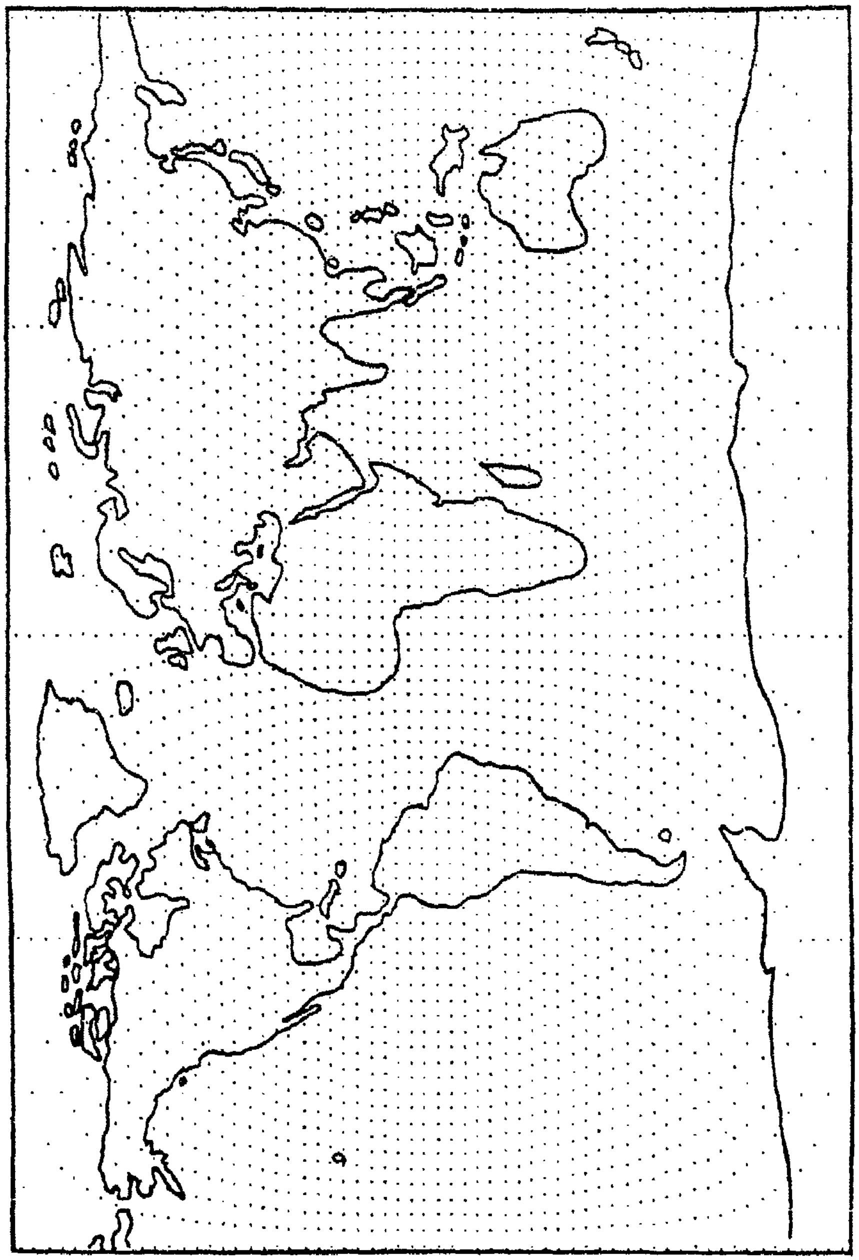

Figure 17. The Kurihawa Grid. This is the internal grid used by HIRAS (from Stobie, 1986).

The first step in spectral transformation is to take the First-Guess 30-wave spectral coefficients, transform them into gridpoint values, and place them on the coarser HIRAS grid. When this is completed, the model performs its OI. When the OI is completed, the model transforms its gridpoint analysis into 40-wave spectral coefficients. Although the analysis is done using gridpoints, the conversion to spectral coefficients allows each gridpoint to affect the entire analysis. In other words, a gridpoint temperature in Ohio could influence a gridpoint temperature in the Caspian Sea. This transformation also allows for the final transformation back to the 2.5° x 2.5° grid. Even though the analysis appears in the database on a 2.5° x 2.5° grid, the true analysis resolution is that of the coarser Kurihara grid that was shown in Figure 17.

Because of deficiencies in the First-Guess model above 100 mb, HIRAS uses the previous HIRAS analysis (6 hours old) for its first-guess instead. The model forces the winds above 100 mb to be geostrophic and uses only horizontal OI above 100 mb--that is, it doesn't look up or down to interpolate data at higher or lower levels. As a result, the analysis above 100 mb is two-, rather than three-dimensional.

4.4.2 The HIRAS Surface Analysis derives 1,000 mb temperature and geopotential height fields from the surface temperature and pressure fields. It is used primarily to anchor satellite sounding data, which includes a great deal of information for the different mandatory pressure levels, but lacks the geopotential height of each pressure level; therefore, the 1,000-mb height fields from the HIRAS surface analysis are used to determine the height of the 1,000-mb pressure level in the satellite soundings. The rest of the pressure-level geopotential heights can be determined from this value.

The surface analysis is also an OI analysis. It differs from its upper-air counterpart because it performs its analysis directly on the 2.5° x 2.5° grid. It does not use spectral transformation or internal grids. It uses the OI error fields to ensure grid data accuracy, but observations are weighted more heavily in the surface analysis than in the upper-air analysis throughout the hemisphere.

4.5 Quality Control. Since observation errors are routine, manual and automated quality control (QC) must be performed. Bad observations must be corrected or discarded in order to prevent the model from providing a bad analysis. QC is accomplished in two ways:

4.5.1 Manual QC is performed by AFGWC forecasters, who delete, change, or create observations based on known information. This forecaster-edited data is known as "bogus" data.

4.5.2 Automated QC. An automated QC system is built into the model. The system can recognize a bad observation (e.g., a 990-mb sea-level pressure within a 1,046-mb high) and discard that observation. There are two steps to this process:

- ***Gross Checks.*** Observations are compared to adjacent gridpoint data from the First-Guess model output. If there is a large enough disagreement, the observation is discarded. If it just barely passes the gross check, it is held over for the second, or "buddy" check.

- **Buddy Check.** An observation that barely passes the gross check is compared with stations nearby; if the observation disagrees significantly, it is thrown out.

Chapter 5

THE GLOBAL SPECTRAL MODEL (GSM)

5.1 Introduction. The GSM (AFGWC's primary forecast model) was designed primarily as an aviation model. There are two GSM models in use at AFGWC; the GSM proper and the First-Guess. The GSM and the First Guess are run every 6 hours. The GSM proper produces forecasts out to 96 hours and First-Guess out to 12 hours. Although the GSM provides a wide variety of forecast fields (see Tables 2 and 3), its main purpose is to provide height, wind, and temperature forecasts for aviation customers. The First-Guess model differs slightly from the GSM. The material in this chapter includes the First-Guess forecast model unless otherwise specified.

5.2 Spectral Forecasting. A true spectral representation uses mathematical combinations of sines and cosines to represent patterns of meteorological fields. That is, a spectral equation contains a series of terms, each having either a sine or cosine term as a factor. Because sines and cosines look like waves, spectral representations are often discussed in those terms; the GSM, for example, is a 40-wave model, even though it uses many more than 40 sine and cosine terms. In fact, to represent a single variable at just one atmospheric level, the 40-wave GSM needs 3,444 terms. This is because the waves are two-dimensional--each wave requires at least one sine and one cosine term. For mathematical reasons, the 40-wave model has 41 sines in one dimension and 42 cosines in the other. Basically, a spectral representation finds the best mathematical terms using the sine and cosine to describe the wave motion of the observed atmosphere.

5.3 Resolution. As already mentioned, the GSM is a 40-wave spectral model (the First-Guess forecast model is 30-wave). This means that the GSM can recognize 40 different trough-ridge combinations in an east-west direction. Its application in the north-south plane is much more difficult to describe without the mathematics, but one way to describe the approximate resolution of the GSM is to think of the grid on which the data is stored.

The grid is adapted to a 40-wave spectral resolution and is used for some of the internal calculations. Based on the grid, its approximate resolution in the north-south direction is 270 km; in the east-west direction, 350 km. The smallest scale feature that can be seen, then, is about 270 km long and 350 km wide. This is only true for a surface low or an upper-level trough; if the feature were a complete wave (trough-ridge combination), the smallest feature resolvable would be twice that size. The resolution of the First-Guess forecast model is slightly lower.

TABLE 2. The Fields Produced by the First-Guess. Many other fields are processed through algorithms on SDHS. THe list includes the levels/layers for which the data is available. All the fields listed are available for the 00-, 06-, and 12-hour forecast.

FIELDS directly forecast	Height/Layer in Millibars
Relative Humidity	sfc, 1000, 850, 700, 500, 400, 300
Heights	1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
Temperature	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
U-Component wind	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
V-Component wind	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10
FIELDS derived	**Height/Layer in Millibars**
Temperature Advection	850, 500, 300
Specific Humidity	sfc, 1000, 850, 700, 500, 400, 300
Tropopause Height	*
Sea Level Pressure	sfc
Dewpoint	sfc, 1000, 850, 700, 500, 400, 300
Vorticity Advection	500
Vorticity	850, 500, 300
**Packed U-V Winds	sfc, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10

* Tropopause data varies with respect to its exact position.

** Packed U-V Winds - the individual U and V wind components contain too many bits of information and must be compacted for SDHS to use them.

TABLE 3. The Fields Produced by the Global Spectral Model (GSM). The first five are forecast directly. The rest are derived from the first five. Many other fields (thickness, omega, height falls, etc.) are processed through algorithms on SDHS. The lists include the levels/layers for which the data is available. (*TP = Tropopause, **GL = Gradient Level)

Level in Millibars	Heights/D-values																						
*TP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	X																						
20	X																						
30	X																						
50	X																						
70	X																						
100	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
150	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
200	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1000	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
sfc																							
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	U and V Wind Components																						
10	X																						
20	X																						
30	X																						
50	X																						
70	X																						
100	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
150	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
200	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
1000	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
sfc																							
**GL				X	X																		
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued...

Level in Millibars	Relative Humidity																					
*TP																						
10																						
20																						
30																						
50																						
70																						
100																						
150																						
200																						
250																						
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1000	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
sfc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	Packed U and V Winds																					
10	X																					
20	X																					
30	X																					
50	X																					
70	X																					
100	X	X	X	X	X		X		X		X		X		X		X				X	X	
150	X	X	X	X	X		X		X		X		X		X		X				X	X	
200	X	X	X	X	X		X		X		X		X		X		X				X	X	
250	X	X	X	X	X		X		X		X		X		X		X				X	X	
300	X	X	X	X	X		X		X		X		X		X		X				X	X	
400	X	X	X	X	X		X		X		X		X		X		X				X	X	
500	X	X	X	X	X		X		X		X		X		X		X				X	X	
700	X	X	X	X	X		X		X		X		X		X		X				X	X	
850	X	X	X	X	X		X		X		X		X		X		X				X	X	
1000	X	X	X	X	X		X		X		X		X		X		X				X	X	
sfc	X	X	X	X	X		X		X														
**GL				X	X																		
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued...

Level in Millibars	Temperature																					
*TP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
10	X																						
20	X																						
30	X																						
50	X																						
70	X																						
100	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
150	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
200	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1000	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
sfc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	Specific Humidity																					
10																							
20																							
30																							
50																							
70																							
100																							
150																							
200																							
250																							
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1000	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
sfc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued.....

Level in Millibars	Dewpoint																					
10																						
20																						
30																						
50																						
70																						
100																						
150																						
200																						
250																						
300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
400	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
500	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
700	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
850	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
1000	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
sfc	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	Streamline Functions																					
10																						
20																						
30																						
50																						
70																						
100	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
150																						
200	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
250																						
300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
400																						
500	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
700	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
850	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
1000	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
sfc																						
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued...

Level in Millibars	Vertical Velocity																						
10																							
20																							
30																							
50																							
70																							
100																							
150	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
200	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
250																							
300	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
400																							
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
1000																							
sfc																							
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	Vorticity																						
10																							
20																							
30																							
50																							
70																							
100																							
150																							
200																							
250																							
300																							
400																							
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700																							
850																							
1000																							
sfc																							
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued...

Level in Millibars	Vorticity Advection																						
10																							
20																							
30																							
50																							
70																							
100																							
150																							
200																							
250																							
300																							
400																							
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700																							
850																							
1000																							
sfc																							
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Level in Millibars	Temperature Advection																						
10																							
20																							
30																							
50																							
70																							
100																							
150																							
200																							
250																							
300										X	X	X	X	X	X	X	X	X	X	X	X	X	
400																							
500	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700																							
850										X	X	X	X	X	X	X	X	X	X	X	X	X	
1000																							
sfc																							
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

TABLE 3, continued...

Level in Millibars	Precipitable Water (layers)																						
500 to 700	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
700 to 850	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
850 to sfc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
HR	00	03	06	09	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	72	96

Tropopause Pressure
Available from 00- to the 60-hour forecast in three hour increments, and for the 72-hour forecast.

Sea Level Pressure
Available from 00- to the 60-hour forecast in three hour increments, and for the 72-hour forecast.

In the vertical, the GSM is a 12-layer model. It uses a vertical coordinate scheme called "sigma levels." The height of the sigma coordinates vary with the terrain. Unlike constant-pressure levels, sigma levels never intersect the ground. The levels are closer together at about 250 mb. The highest GSM vertical resolution is between 500 mb and 200 mb (see Figure 18) because the GSM is an aviation model and most aircraft fly at about 250 mb. There are only two levels above 100 mb.

The GSM uses data fields from the HIRAS model's 2.5° x 2.5° latitude-longitude grid for its initial conditions. The HIRAS data is stored in the database on the GSM's 2.5° x 2.5° grid. It undergoes a spectral transformation for use by the GSM in making its forecast. When complete, the data is interpolated back to the 2.5° x 2.5° grid for storing. Currently, most display programs require that the data be displayed on a PST map projection; this requires the data to be interpolated from the 2.5° X 2.5° degree grid to the whole-mesh subgrid and results in a further decrease in data resolution. Products produced at AFGWC on SDHS (or for transmission over AWDS or facsimile circuits) are based on the lower resolution whole-mesh subgrid.

5.4 Normal Mode Initialization. Before the GSM can use the HIRAS analysis data for its initial conditions, it must undergo a process called "Normal Mode Initialization," or NMI. The main purpose of the NMI is to prevent the model from becoming mathematically unstable due to inherent instabilities in the input data that are a result of minor perturbations the model can't resolve. These perturbations may be real (small-scale phenomena), fictitious, or due to small observation errors. Almost all models use some form of NMI.

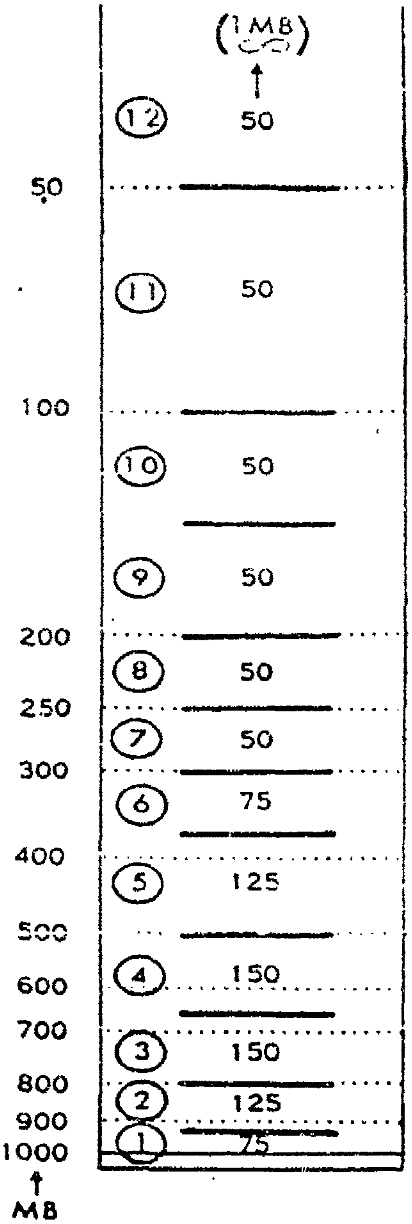

Figure 18. The Sigma Levels of the Global Spectral Model. This is the vertical resolution of the model. Note the higher concentration of layers between 500 and 200 mb. The forecast of some elements is conducted directly on the layer boundaries (indicated by the thick horizontal lines). The rest of the forecast is conducted in the center of mass between the layer boundaries (from Stobie 1986).

5.5 Small-Scale Diffusion. This mechanism is used during the running of the model; it also is intended to keep it from becoming mathematically unstable. Diffusion dampens the higher frequency horizontal waves (e.g., gravity waves) that the model can't resolve. A simplistic way to put it is that it smooths the data fields very slightly. In the GSM, the need for small-scale diffusion is not great, since the GSM does not cycle back on itself--that is, the GSM does not use its 12-hour forecast to initialize the next forecast run. The First-Guess model, on the other hand, *does* cycle back on itself and therefore requires much more diffusion.

5.6 Topography. The topography incorporated in the GSM is much smoother than actual terrain (see Figure 19). There are no jagged peaks nor deep valleys, and the Earth appears to be composed of rolling hills. Again, the main reason for using the smoother topography is to prevent the model from becoming numerically unstable. Real terrain data would create features within the forecast that the model could not resolve. Another reason for the use of the smoothed terrain is to optimize the forecasting capability of the computer, given the limited memory and CPU available.

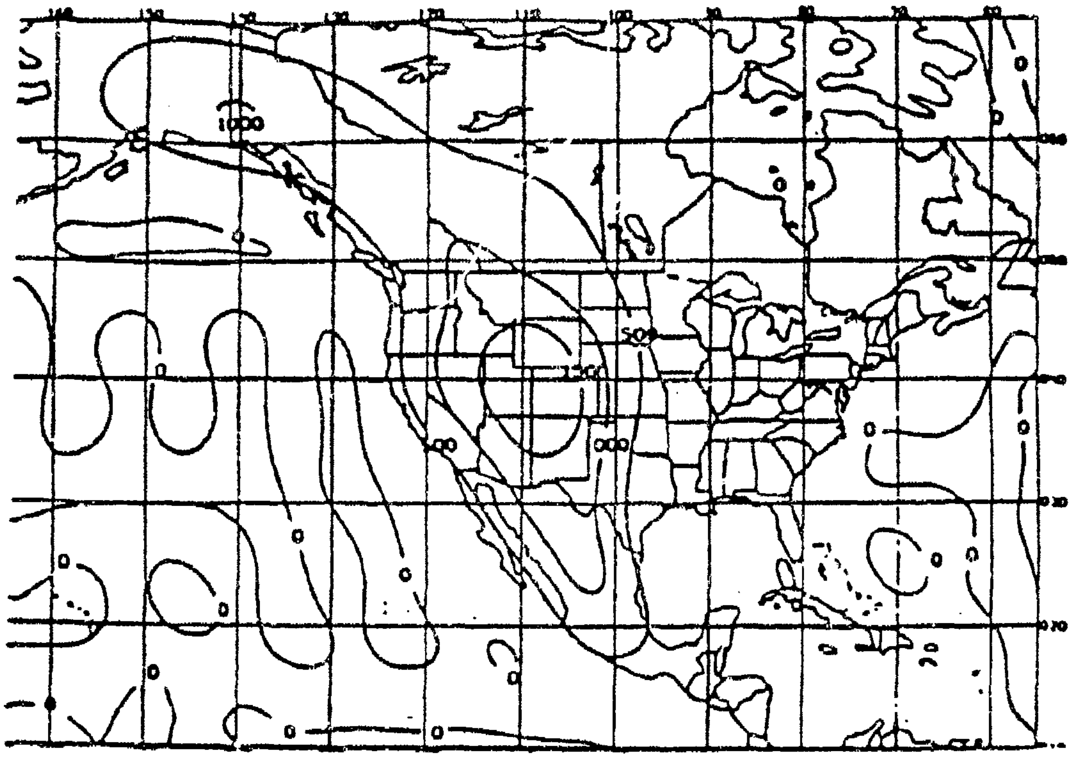

Figure 19. The Topography of North America as Seen by the GSM. The heights are in meters (from Stobie, 1986).

5.7 Surface Friction. Because of surface friction, winds in the GSM are generally non-geostrophic. Over major mountain chains (such as the Rockies and Himalayas) surface friction is considered to be five times stronger than over oceans.

5.8 Sensible Heat Exchange. In the GSM, the atmosphere receives sensible heat only from the oceans. No heat is exchanged over land surfaces. Sensible heat released into the atmosphere is dependent on temperature differences between the water and the air, and on the surface wind speed. If the water is warmer than the air, heat energy is transferred from the water to the air, and vice-versa. When strong winds are forecast, the sensible heat exchange is two to three times higher than during calm conditions. The heat received or lost by the atmosphere is based on monthly climatological sea-surface temperatures. When an El Niño (or another dramatic anomaly in sea-surface temperature) occurs, the GSM will not accurately represent the sensible heat exchanges; the result is an occasional forecast error in cyclone strengthening or weakening. The GSM would only recognize the heat already exchanged into the atmosphere as evidenced by the analysis.

5.9 Evaporation. Only moisture from the oceans can be evaporated; the GSM does not take soil moisture evaporation into account. Evaporation is based on monthly climatological sea-surface temperatures and forecast surface wind speeds. Stronger winds result in increased evaporation. Because of these limitations, GSM moisture forecasts are typically too dry, especially over land.

5.10 Precipitation Effects. The GSM forecasts two types of precipitation: *synoptic* (large-scale) and *cumulus* (small scale). Evaporation and the release of latent heat resulting from precipitation are taken into account during the model forecast process. The GSM is not considered a superior precipitation model and these processes don't help the moisture forecasts. The real purpose of GSM precipitation forecasting is to forecast the effects of precipitation on other forecast elements; that is, to quantify latent heat release and evaporation and determine its effects on temperature and wind.

5.11 Radiation. This energy source currently does not exist in the GSM; there is no radiation cooling at night nor insolation during the day. Although the net result is a warm bias in the model, it is not considered overly significant in the short range (3 days or less). The First-Guess forecast model is much more vulnerable to the lack of radiation processes because it cycles back on itself. The problem is kept under control through Optimum Interpolation by blending the First-Guess forecasts with observations every 6 hours.

5.12 GSM Performance. Not much has been written on the GSM's capabilities and weaknesses. Most of the data for the following notes on GSM performance was collected from statistical processes, but some of the information is based on discussions with AFGWC/SYS meteorologists.

- Long waves are handled well, considering that the model was designed for flight-level forecasting.

- Forecast wind speeds are typically too slow below the 100-mb level.

- Moisture forecasts are typically too dry.

- The GSM is generally too warm in the troposphere.

- Since the GSM forecasts geopotential heights balanced with temperature, the geopotential heights are generally too high.

Chapter 6

THE REAL-TIME NEPHANALYSIS MODEL (RTNEPH)

6.1 Introduction. The main purpose of the RTNEPH model is to initialize the cloud forecast models. RTNEPH uses an eighth-mesh grid. Its horizontal resolution is about 48 km at 60° N. RTNEPH has only four levels in the vertical. These levels are not fixed, but are sorted by cloud base; the highest base is at level one. The four levels are not necessarily continuous horizontally, and may be at different levels for each gridpoint. If there are more than four cloud layers, extra layers are merged with the next closest. Up to eight layers can be merged to fit into the four available levels per grid point. If there are more than eight layers, the lowest will not be accounted for. Levels can range from the surface to 21,900 meters (71,932 feet) MSL. The vertical precision can be as fine as 30 meters between levels below 6,000 meters and 300 meters between each level above 6,000 meters.

6.2 RTNEPH Production Cycles. There are three RTNEPH production cycles: *sprint, non-sprint,* and *update*. The sprint cycle is only used when support requirements demand it. The other two are run every day. Unlike HIRAS, the RTNEPH data base is updated continuously using these three cycles.

6.2.1 The Sprint Cycle. The purpose of the sprint cycle is to take a quarter orbit of satellite data as soon as it is received and incorporate it into the RTNEPH analysis for immediate use in the short-range cloud forecast model. The sprint cycle is quality-controlled manually as needed. Changes are made with bogus data. Bogus data is information manually given to the analysis model to counter the negative affects of bad conventional or satellite data. The sprint cycle only updates that portion of the RTNEPH analysis for which satellite data is available, but both satellite and conventional data are used to update the RTNEPH for these points.

6.2.2 The Non-Sprint Cycle. The non-sprint cycle is the same as the sprint cycle except for the time factor. Immediate cloud forecast model input and manual quality control are not needed. The non-sprint cycle is still triggered by the receipt of a quarter-orbit of satellite data. Like the sprint cycle, it only updates that portion of the RTNEPH analysis for which satellite data is available. The non-sprint cycle also uses satellite and conventional data to update the RTNEPH.

6.2.3 The Update Cycle. The update cycle is run every 3 hours to incorporate as much data into the RTNEPH database as possible. Unlike the other two cycles, the update cycle updates the entire Northern and Southern Hemispheres during its run. The Northern Hemisphere is updated 1 1/2 hours after data time; the Southern Hemisphere, 2 1/2 hours after data time. Conventional data is the primary input because the satellite data (received in quarterly segments) has, for the most part, already been used to update the analysis. All conventional data received from both hemispheres is incorporated; in the other two cycles, conventional data is only used for the quarter orbit being processed.

6.3 Analysis Modes. There are three types of RTNEPH analyses: *conventional, satellite,* and *persistence.*

6.3.1 Conventional Analysis. Since surface observations are updated in the database every hour, the conventional cloud analysis is also performed once an hour. This allows for the most recent data to be available whenever the Merge Processor (to be explained later) needs it. Conventional data is only used at those gridpoints for which it is available. OI is not performed.

Conventional cloud data from upper-air and surface synoptic, METAR, and AIRWAYS reports is used (including the data unique to each type of observation). If more than one source of conventional data is available, conflicts are resolved by taking into account the data's timeliness and reliability. Surface-based observations are considered more reliable than upper-air soundings for the same point. All hourlies and special observations 3 hours prior to analysis are considered.

When cloud amounts are reported as scattered, broken, or overcast in surface reports, the data is stored directly and assigned 25, 75, and 100% coverage values, respectively. Cloud bases reported in Airways code are converted to meters. Because cloud information in synoptic observations is limited, cloud height *categories* are used (i.e., surface to 6,500 feet, 6,500 to 22,000 feet, and 22,000 feet and above). If a cloud type is not observed, zero percent probability is assigned to the corresponding height category. When a valid cloud type is given, 100% probability is assigned. For missing cloud types, 50% probability is assigned.

Present weather is also used to determine cloud base heights and types. Only one type of precipitation (the most significant) can be included in the RTNEPH database for each gridpoint. It is maintained in the database as a separate element.

Model terrain is used to change AGL to MSL; this only affects data for individual gridpoints.

6.3.2 Satellite Analysis. Satellite information is only used when polar orbiting data (infrared and/or visible) is available. The threshold method for determining cloud cover from satellite data is the basic method used. Background brightness fields are used as a starting point for a histogram. The ability to tell the difference between cloud cover and background is extremely dependent on these fields, which change with sun angle and reflectivity (snow/ice) and must be updated. Sensed brightness of a pixel determined to be clear is compared with the background brightness, which is adjusted so that it approaches the value of the new sensed value without straying too far from the current background brightness values.

In general, darker (less bright) visual data is associated with cloud-free areas. Conversely, brighter data is associated with cloudy areas, but brighter values may also be associated with terrain albedo affects, or snow and ice. Infrared data represents temperature in terms of brightness. In RTNEPH, brighter infrared measurements indicate lower temperatures. Although both visual and infrared provide brightness values indicating amounts of reflected or radiated energy, the determination of cloud cover requires a comparison of the satellite data to the expected background brightness. For visual data, the background is a variation of surface albedo. Therefore, if the sensed data is *brighter* than the background, clouds are present. For infrared data, background brightness is based on surface temperature; if the sensed data is *colder* than the adjusted background surface temperatures, clouds are present.

When visual satellite data is received by RTNEPH, the pixel data would appear as shown in Step 2 of Figure 20. Step 3 shows an array of the visual brightness values for the pixel gray shades from the Satellite Global Database (SGDB). Step 4 shows the resultant histogram, which gives frequency of occurrence for the possible gray shades.

After the histogram is formed, the expected background brightness, (the value of 5 represents a water background in this example) is compared to the histogram. All pixels with a value higher/brighter than the expected background are considered "cloudy" pixels.

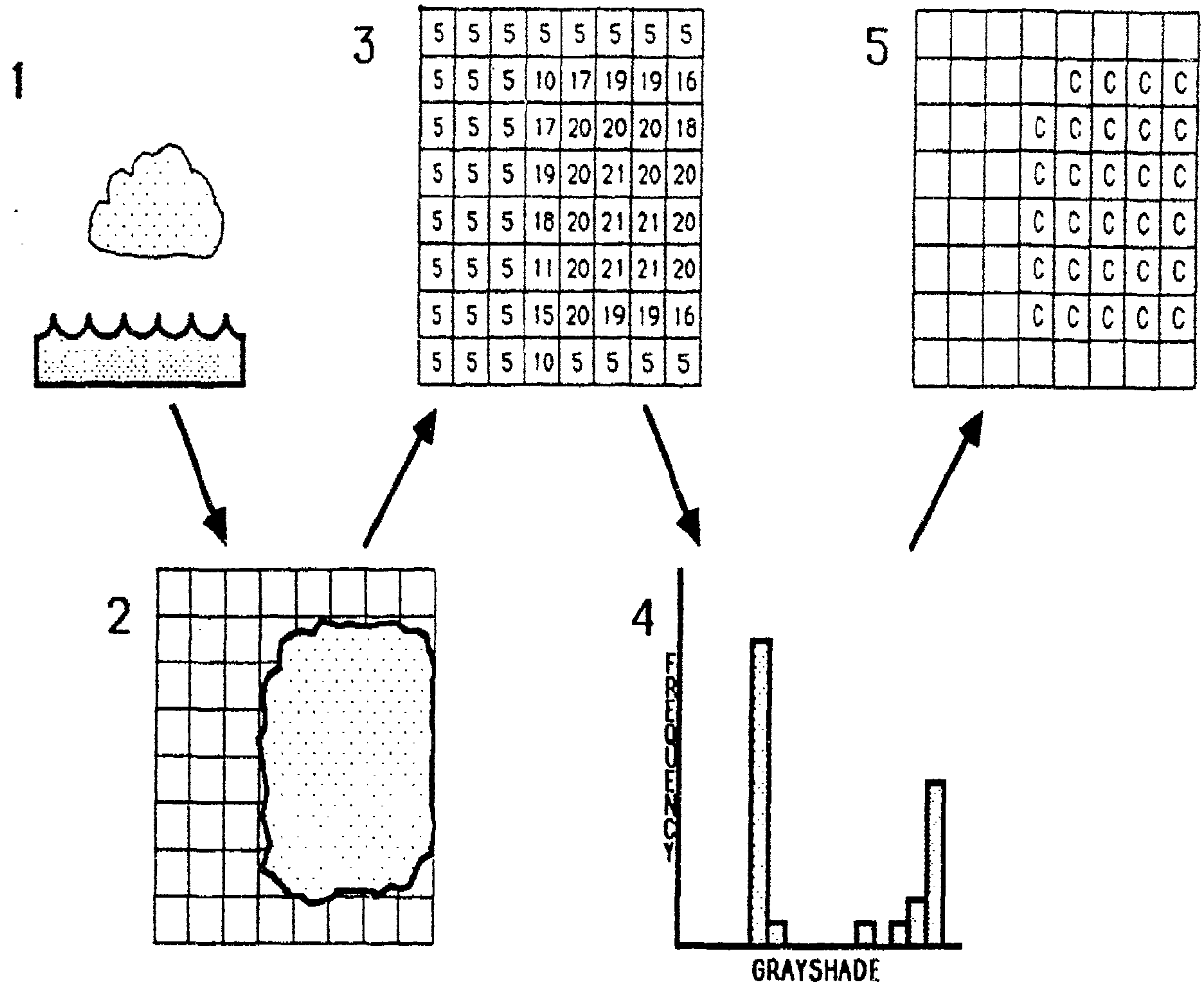

Figure 20. A Pictorial Example of How Cloudy Pixels are Determined by the Satellite Processor (from Kiess and Cox, 1988).

6.3.3 Persistence Analysis. The RTNEPH persistence analysis is simply one that is equal to the previous analysis. The persistence analysis is used when no new data is available.

6.4 The Merge Processor.

The three analyses described above are computed in three separate processors. When completed, they are blended together in the merge processor. Since conventional data is input only at the gridpoints for which they are available, and since satellite data is input only where it is available, there will be some areas with no data; these are where the persistence data will be input. When the merge processor is finished, it provides an updated global nephanalysis database. The merge processor also reconciles conflicts between conventional and satellite data at the same grid point.

6.4.1 Bogus Data. If bogus data is available for a particular gridpoint, it will replace all other data only if timeline requirements are met.

6.4.2 Data Spreading. The merge processor also considers conventional data that can be spread to other gridpoints. Data is spread from gridpoints that are flagged as "best report" gridpoints using the following guidelines:

- Data will be spread only to those gridpoints within an allowable spread radius.

- Data is spread from the nearest, "best report" gridpoint.

- If the distances between two "best report" gridpoints are equal, the newest report is used. If they have the same time value, the least cloudy report is used. If they are equally cloudy, the one with the greatest visibility is used. If no tie breaker is found, then the first "best report" considered is used.

6.5 RTNEPH Deficiencies.

- When only satellite data is available, RTNEPH under-interprets low clouds because the infrared threshold becomes larger than the temperature difference between the clouds and the ground or between the ground and the modeled ground temperature.

- Over- or under-interpretation may occur along coastlines due to problems in choosing a representative background brightness or temperature to represent the gridpoint during the satellite analysis. For example, sea and land surface temperatures are almost always different. The satellite processor building the histogram may use higher daytime land surface temperatures as a background over the water and therefore see clouds where there aren't any.

- Snow and ice fields are incorporated into RTNEPH by the SNODEP model. If the snow and ice data is incorrect, the RTNEPH might analyze stratus instead of snow.

- High plateaus (such as the Tibetan Plateau) are generally over-interpreted because of their lower surface temperatures.

- Small-scale clouds are usually under-interpreted due to the satellite pixel resolution.

Chapter 7

THE 5LAYER MODEL

7.1 Model Description. The 5LAYER Model produces forecasts of clouds, temperatures, and other elements at 3-hour time steps out to 48 hours in the Northern Hemisphere and out to 24 hours in the Southern Hemisphere. 5LAYER produces forecasts on an octagon half-mesh grid. It does not completely cover the tropics. 5LAYER forecasts for the following atmospheric layers:

- The gradient-level layer (600 to 987 meters AGL)
- The 850-mb layer (987 to 2,235 meters MSL)
- The 700-mb layer (2,235 to 4,238 meters MSL)
- The 500-mb layer (4,239 to 7,368 meters)
- The 300-mb layer (7,368 meters MSL and above).

Before running a forecast, 5LAYER compacts (or smooths) the eighth-mesh RTNEPH analysis into a half-mesh, 100-NM resolution grid analysis. RTNEPH, GSM, and HIRAS are the primary data sources for 5LAYER, which uses dew-point depression, static stability, and cloud type to produce forecasts of clouds, precipitation amount, precipitation type, and icing.

7.2 Resolution. As its name implies, 5LAYER forecasts for five layers in the vertical on a half-mesh grid with a horizontal resolution of 190.5 km at 60° N. Although the resolution of 5LAYER forecasts is about equal to that of many operational dynamic models, the forecasts are smoothed considerably compared to raw satellite data, which resolves cloud elements to 3 km. The lower 5LAYER resolution results in a final forecast that represents average cloud conditions within a large volume. In later discussions, this volume is referred to as a "parcel." Vertical atmospheric layers (850 mb, 700 mb, 500 mb, and 300 mb) are fixed, while the gradient level follows terrain. Fixed levels may intersect the ground at higher elevations where the gradient layer is above 850 or 700 mb.

7.3 The Quasi-Lagrangian Advection Scheme. The model makes its forecast by advecting parcels (or volumes) of the atmosphere using a quasi-Lagrangian advection scheme--essentially a trajectory forecast. A true Lagrangian scheme takes a parcel from the initial point to its destination at the end of the entire forecast period. The 5LAYER takes a parcel from its initial point to the first 3-hour time step, then to the next 3-hour time step, and so on. The RTNEPH provides the initial cloud information for each gridpoint. The GSM provides the winds for the initial time and for each 3-hour time step, and HIRAS provides the initial temperature and moisture conditions. 5LAYER modifies air parcels as they move through the trajectory path to the 3-hour point. The 3-hour forecast then becomes the initial state for the next 3-hour forecast. This process is repeated until the desired forecast length (48 hours) is reached.

7.4 Initializing the 5LAYER. The RTNEPH analysis provides cloud top, base, and amount information for each layer at each gridpoint. Total cloud coverage (in percent) is also provided. In order to initialize 5LAYER using RTNEPH data, the four non-fixed levels of the RTNEPH analysis data must be matched to the five layers of the forecast model. The data must also be compacted (from the RTNEPH analysis eighth-mesh grid to the 5LAYER half-mesh grid) to reduce the volume of data while retaining most of the larger-scale information.

The compaction takes data from the 25 eighth-mesh gridpoints and applies it to the one half-mesh gridpoint they surround. It uses a grid-weighting system in which all points that immediately surround the gridpoint on the 5LAYER have equal weight; eighth-mesh gridpoints farther away from the 5LAYER half-mesh gridpoint affect it to a lesser degree. This process degrades the analysis because data averaging results in a loss of distinction between moist and dry air. To spread the clouds vertically, the top and base of each RTNEPH cloud layer is checked to determine which 5LAYER fixed layers they overlap. RTNEPH cloud layer amounts are inserted into 5LAYER fixed layer gridpoints unless the receiving gridpoints already have a larger cloud amount. For 5LAYER to use the eighth-mesh RTNEPH analysis, it would need to initialize 2,621,440 grid points (262,144 grid points/hemisphere times two hemispheres times five layers). Computer hardware and AFGWC time constraints make it impossible for a prediction model to use eighth-mesh gridpoints at this time.

7.5 Old Data Limitations. In areas where the RTNEPH is too old (by 4 hours or more), 5LAYER uses its previous forecast as an initial condition, or analysis. This commonly occurs in extratropical areas where polar orbiting satellite data can be 5 1/2 hours old, or more. Fast-moving cloud systems result in a loss of distinction between cloudy and dry air due to the persistence forecast initialization process in areas of old data.

7.6 Initializing the RTNEPH. Total cloud amount for a particular vertical grid stack is computed from the statistical union of layer cloud amounts, maximum layer cloud amount, and average layer separation. To help understand this, let's assume that there are two layers, both with 50% cloud coverage. If they are separated by 11,000 meters (assumed to be the depth of the troposphere) the layers are considered *uncorrelated*--the total cloud amount for the stack is 97%. If the two layers are immediately adjacent to one another, they are considered *correlated*--the total cloud amount is equal to the maximum cloud amount of the individual layers, or 50%.

If 11,000-meter separation of layers provides a 97% total cloud amount, and if immediately adjacent layers result in cloud amounts equal to the maximum cloud amount between the two layers in percent, layers with separations between these two figures are computed proportionally--that is, 50% maximum cloud with two layers; 6,500-meter separation equals about 74% total coverage.

Where more than two layers are found, the average of all possible pair-wise separations of the cloud layers is divided by 11,000, then subtracted from 1 to derive the percent of total cloud; 1 is equal to 100%. This new cloud amount is used to adjust the 5LAYER amounts to match reality (the RTNEPH). If the total cloud amount is not close enough to the analyzed total as compared to RTNEPH, they are considered to be out of tolerance and corrected with a computation that includes the RTNEPH total cloud amount.

7.7 Condensation Pressure Spread (CPS) is the moisture variable used by the 5LAYER. CPS is the difference in pressure (millibars) between a parcel and the pressure to which it needs to be lifted for condensation to occur. 5LAYER assumes that if a parcel is lifted to a low enough pressure, condensation will occur. CPS correlates directly to dew-point depression. Although dew points are not advected, parcels are moved in a trajectory; dew points are dependent on the pressure of the parcel at the end of the forecasted move. Since the RTNEPH can't determine the moisture content of cloud-free areas, either the default CPS or the CPS derived from the GSM (whichever is drier) is used to fill the gaps around cloudy areas. CPS is also the link between the cloud amount data received from RTNEPH and the GSM dew-point data, making it a "common to both" moisture variable.

For example, a CPS of 5 would equal 97% cloud coverage and a dew-point depression of zero. An advantage to having a CPS is that it correlates changes in cloud amount with changes in vertical motion. If an unsaturated parcel is lifted, adiabatic cooling takes place, the dew-point depression narrows, and clouds form. For downward motion, the dew-point depression widens and clouds dissipate.

The cloud amount can be determined directly by the net vertical displacement of the parcel in terms of pressure. If supersaturation occurs due to the modification of a parcel along its trajectory, the excess moisture is condensed and added to the quantitative precipitation.

7.8 Cloud Type Determination. Determination of cloud type in the 5LAYER is a relatively simple process. Cumuliform or stratiform type clouds are determined by the stability of the 850-, 700-, and 500-mb layers. For example, if the wet-bulb potential temperature of the 700-mb layer is less than that of the 850-mb layer, positive (upward) buoyancy in the 700-mb layer is assumed.

When there is *positive* buoyancy in a layer containing clouds, the cloud type is cumuliform; if there is *negative* buoyancy, the cloud type is stratiform. If, in a vertical column, there are clouds in a negatively buoyant 700-mb layer, the cloud type is altostratus; if the 700-mb layer is positively buoyant, the cloud type is altocumulus.

If the 850-, 700-, and 500-mb layers are positively buoyant and all three contain clouds, the cloud type is cumulonimbus. If the column is negatively buoyant, cloud type is nimbostratus. Cirrus-level clouds are considered simply "cirrus," not cirrostratus or cirrocumulus.

7.9 Precipitation Type Determination. Cloud type, as determined IAW 7.8, is primarily used in determining precipitation type. Other variables used are amount of cloud cover and static stability.

Showery precipitation requires the presence of towering cumulus or cumulonimbus, and at least 25% cloud cover. To forecast snowshowers, the gradient level layer temperature must be 0° C. The *intensity* of showery precipitation is determined from the static stability, which is determined by computing the Showalter stability index for gridpoints with terrain heights below 850 mb. For terrain above 850 mb, stability is determined in the same way as for cloud type. In areas of cumulonimbus, the Total-Totals stability index is used.

Diurnal heating and orographic effects are not considered in determining precipitation type. Continuous precipitation is forecast if cloud cover is at least 75% and there are cloud types other than cumulonimbus or towering cumulus in the 850- and 700-mb layers.

The snow/rain distinction is made in the same way as for showery precipitation. Intensity determination is a function of total moisture depth and the buoyancy of the 700-mb layer; the greater the total moisture depth and 700-mb buoyancy, the greater the precipitation intensity.

7.10 Temperature Initialization. The initial temperature field needed for the 5LAYER forecast is input from the HIRAS analysis and converted from the HIRAS 2.5° x 2.5° degree grid to a whole-mesh grid. which is then converted to the half-mesh grid used by the 5LAYER. The temperatures are interpolated directly to each of the four pressure levels that define the midpoint of the fixed model layers.

The terrain-following gradient level is initialized using a height interpolation between fixed pressure levels in HIRAS to ensure that gradient-layer temperatures are relatively free from small-scale local effects.

A trajectory method of temperature advection is used to make temperature forecasts. As trajectories displace parcels, they are modified by several atmospheric processes--the dry adiabatic process is the most important of these, but others include latent heat release, diurnal heating, and turbulent mixing. Some of these processes are not handled by the GSM. The temperature lapse rate at each gridpoint is checked at the end of each time step to make sure a superadiabatic lapse rate was not created.

7.11 Forecast Elements. Temperature and CPS are the only two meteorological elements advected using the trajectory scheme. Other fields derived from these two elements include layered and total cloud cover, dew-point depression, stability, quantitative precipitation, cloud type, and icing.

7.12 Wind Initialization. Wind forecasts from the GSM are used to construct three-dimensional trajectories to determine the path of each air parcel. After the wind forecasts are averaged in time, the trajectories are computed backward from selected gridpoints to their origins. Since the trajectories define the origin of an air parcel, they are computed by starting at the final forecast point. This allows for modification of the parcels through time and space.

7.13 Terrain effects are determined using the half-mesh terrain database. Since the gradient level is terrain following, the wind components received from the GSM may be modified to account for steep terrain, for two reasons:

- First, to prevent an upstream parcel trajectory from backing into the terrain. At the conclusion of each time step, the pressure of the trajectory origin is compared to the interpolated terrain pressure. If the origin intersects (or is below the terrain level), the vertical component of the trajectory is adjusted so that it is exactly 20 mb above the terrain.

- Second, when a large change in pressure occurs in a short time (as when air parcels move over mountains), the model has a tendency to create heavy precipitation on the windward side and counter with extreme dryness on the leeward side. The vertical displacement of each gridpoint is checked to see if it exceeds the 50-mb/3-hour displacement criterion; if it does, the horizontal component of the trajectory is cut by one half and the vertical displacement is recomputed. If the criterion is still exceeded, the horizontal component is again cut by one half and the vertical displacement is computed again. The process is repeated until the displacement value is less than 50 mb/3 hours.

7.14 The 5LAYER Grid. The grid used for the 5LAYER is the octagonal half-mesh that was shown in Figure 5. This poses a problem when trajectory origins are beyond the boundary of the grid. The 5LAYER solves this problem by truncating all trajectories for the sides of the grid that parallel the x-y axis (x is 170° E, 10° W) to the edge of the octagon grid. More complicated mathematics are applied for the diagonal sides. Simplistically put, the diagonal sides are rotated 45°, the truncation is completed, and the sides are rotated back. All trajectories within two whole-mesh grid points (400 NM) of the edge inside the grid boundary are checked to see if this truncation is needed. No parcel from outside the boundary of the grid is allowed to move across the boundary into the grid, and flow is forced to be parallel to the boundary of the grid.

7.15 Trajectory Origins. During the forecast process, trajectory origins rarely fall directly on a gridpoint at one of the fixed layers of the model. Because of this, two forms of data interpolation have been developed: *two-point* and *eight-point*. Using both methods gives a precise description of areas with large amounts of cloud coverage and decreases computer processing time.

- Two-point interpolation is used when the parcel originated from an area where the analysis has 50% cloud cover or less. In the two-point interpolation, a parcel's point of origin is rounded to the nearest vertical gridpoint axis. Data is then interpolated to the point from the nearest two fixed layers. Because of rounding, two-point interpolation tends to be less accurate than eight-point interpolation.

- Eight-point interpolation is used when the analysis shows more than 50% cloud coverage. It is considered more accurate than two-point interpolation because it does not round the origin point to a gridpoint. Eight-point interpolation computes data using every gridpoint horizontally and vertically adjacent to it.

7.16 The Entrainment Process. One problem with true Lagrangian advection is that there can be no interaction between air parcels. An entrainment variable, therefore, has been added to counter this deficiency. The model simulates two types of mixing:

- The first slightly adjusts the CPS of the parcel arriving at the termination point in the trajectory using the original CPS value of that termination point. If the original CPS value is greater, the new CPS will be increased; if the original CPS value is less, the new CPS is decreased. This process is applied to all points. It tends to make the the difference between cloud and cloud-free areas less distinct.

- The second type of mixing only applies when ascending parcels cause cloudy points to become clear or when descending parcels cause cloud-free points to become cloudy. The first step is to determine whether or not the conditions causing these effects warrant mixing. If they do, rising parcels are forced to *enhance* cloud formation and descending parcels are forced to *inhibit* clouds, based on (and proportional to) the surrounding conditions and the rate of vertical displacement.

7.17 Diurnal Effects. 5LAYER incorporates diurnal effects in the cloud forecasting process. It assumes that, with the right proportions of moisture and heating, air parcels will rise. If they reach the lifted condensation level, clouds will form. The diurnal effects variable takes local effects into account, such as those caused by steep terrain features.

7.18 Low-Level Precipitation Evaporation is based on two factors: (1) Very dry air evaporates at a greater rate than moist air, and (2) Large amounts of available liquid water result in large amounts of evaporation. The amount of evaporation is decreased when moist air is present or when available liquid water is lacking.

7.19 Low-Level Moisture Sources. 5LAYER lacks low-level moisture sources, such as the Gulf of Mexico. For this reason, the model has an inherent tendency toward dryness.

7.20 Icing Forecast Variables. The icing forecast produced by 5LAYER is based on criteria in AWS/TR-80/001, *Forecasters Guide on Aircraft Icing.* Initially, all icing intensities are specified as "light." When cold-air advection is forecast to exceed 2 K/3 hours, icing intensity is increased to moderate. When warm-air advection exceeds 0.1 K/3 hours, the intensity is decreased to a "trace." The criteria are built into 5LAYER for forecasting icing, as shown by Table 4.

TABLE 4. 5LAYER Icing Forecast Criteria.

Temperature	Dew-point Depression	Icing Type	Cloud Type
-1 to -7° C	-2° C	Clear or rime	Cumulus or stratus
-8 to -15° C	-3° C	Mixed or rime	Cumulus or stratus
-16 to -22° C	-4° C	Rime	All clouds

Chapter 8

NATIONAL METEOROLOGICAL CENTER PRODUCTION CYCLES

8.1 The Aviation Run (AVN) provides global forecasts of synoptic systems and upper-level winds out to 72 hours. It is performed every 12 hours, but like the AFGWC GSM run, a 6-hour forecast is produced as the First-Guess for the final run, which will be described later. On NMC's CRAY supercomputer, the analysis run takes about 15 minutes; the forecast run, about 80 minutes. When the CRAY is down, the last forecast produced is used as a back-up. If the outage is prolonged, the United Kingdom model and the AFGWC GSM are used as back-up. Because of time constraints, the AVN is not run on NMC's NAS9000 computer. Transmission of the AVN forecast fields begins about 4 hours after database time.

8.1.1 The Spectral Statistical Interpolation Analysis System (SSI). The SSI Analysis System is the new analysis model used for the AVN run; it replaces the Global Optimum Interpolation (GOI) analysis model used previously. The analysis is performed in the Global Data Assimilation System (GDAS). This system (like the Regional Data Assimilation System, or RDAS) couples continuous data collection with a series of analyses. Data cut-off time is H+2:45. The 6-hour forecast produced by the AVN from the previous model run is used as the First-Guess. An analysis is performed every 6 hours.

There are some major differences between SSI analysis and the optimum interpolation (OI) techniques discussed earlier. OI techniques analyze data by gridpoint and by mandatory level. Observations are established for each gridpoint by using conventional data (such as surface observations and rawinsonde), non- conventional data (satellite soundings), and forecast data in a weighted averaging system. SSI, on the other hand, analyzes all data types in spectral space simultaneously. SSI is also capable of incorporating Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) total precipitable water and surface wind-speed data. The NMC Regional Optimum Interpolation (ROI) and the AFGWC HIRAS analyses cannot use these types of data.

The analysis in *spectral* (as opposed to *grid*) space has two major advantages.

First, there is no need to run a normal mode initialization prior to using the data in the forecast models. Most other operational assimilation systems require analyses to be initialized because large-scale gravity waves are produced by imbalances in the mass and motion fields. When initialization is applied to SSI, very small changes are made in contrast to the substantial alteration of OI analyses. False waves in the tropics, for example, are removed from an OI analysis during initialization. The SSI analysis does not produce those features, and it is not necessary to attempt removal.

The second major advantage is that the SSI analysis, accomplished in spectral space, uses levels close to the operational forecast model sigma levels. In OI analyses, a great deal of interpolation is required to convert the mandatory levels of the analysis to the sigma levels of the operational forecast model, resulting in analysis data degradation.

8.1.2 The NMC Global Spectral Model (NMC GSM). The 126-wave NMC GSM is the forecast model for the AVN run. Resolution is about equal to a 105-km grid field (85 km less than the AFGWC half-mesh). Output fields are produced at 6-hour intervals and output on both a 65 X 65 point, 381-km resolution grid (the same as the AFGWC whole-mesh grid) and in spectral coefficient form. The GSM started as a 30-wave model in 1980 and went to 40 waves in 1983 (this was the GSM model acquired from NMC by the Air Force). It was increased to 80 waves in 1988, and went to the present 126 waves in 1991. Its 18 sigma levels, as compared to the 12 levels of the AFGWC GSM, allows higher resolution in the jet and boundary layers. An example of the vertical resolution of the NMC GSM is shown in Figure 21. The NMC GSM uses a mean orography terrain--see Figure 22.

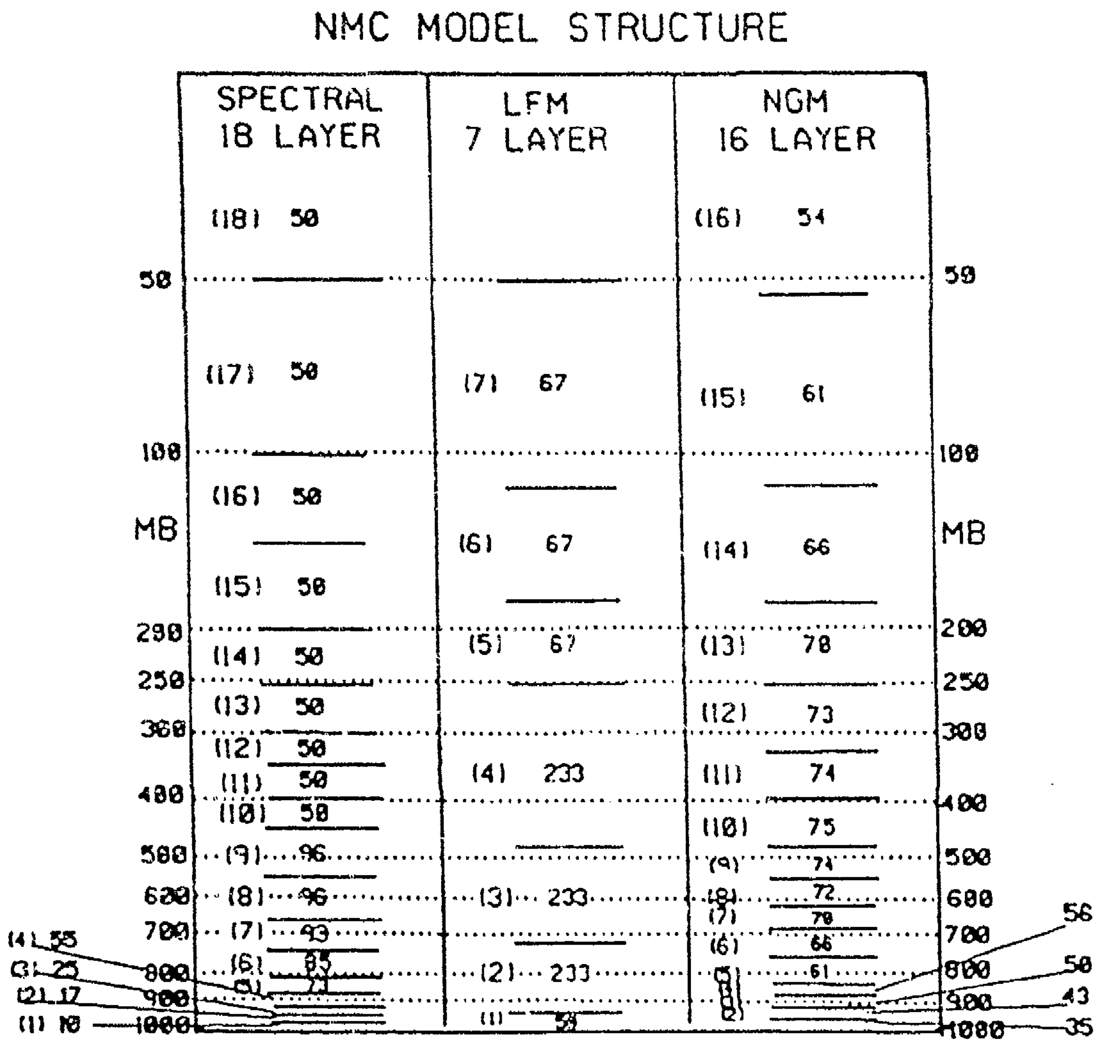

Figure 21. Vertical Resolution of the NMC Spectral Model (AVN/MRF), LFM, and NGM (from Hoke et al., 1989).

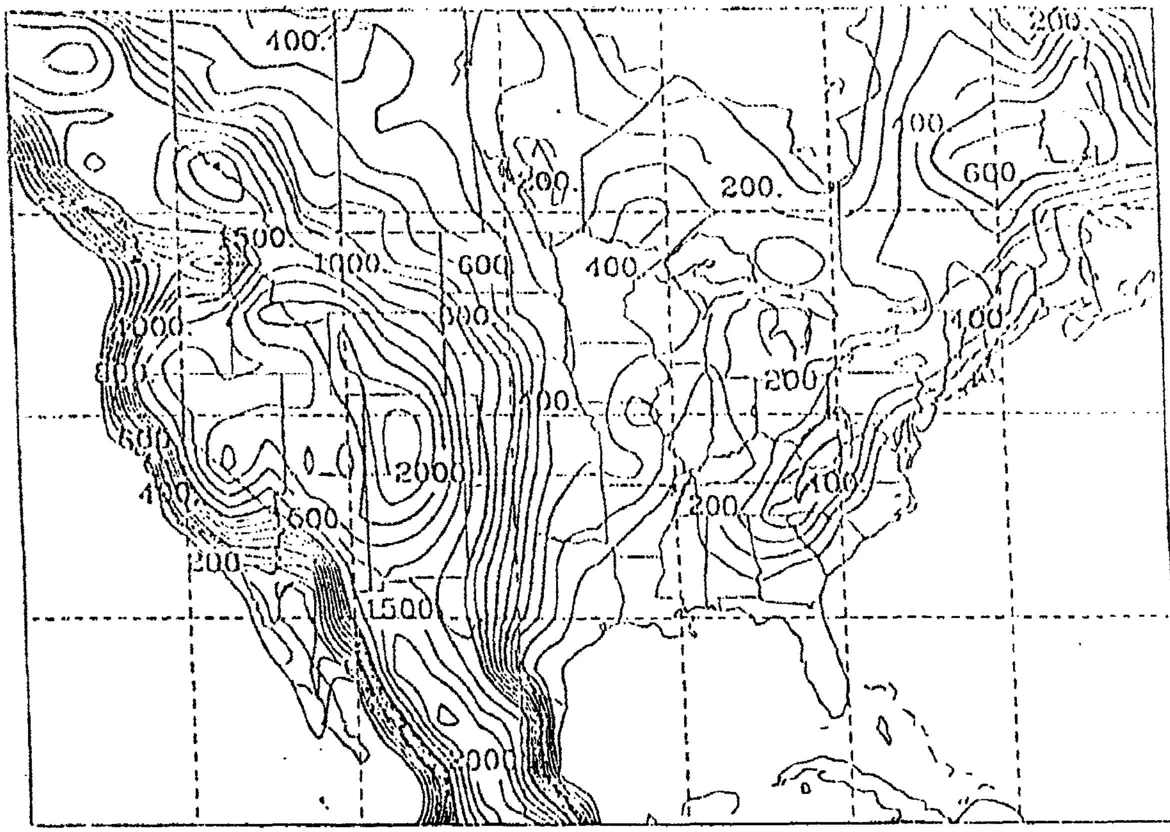

Figure 22. The Topography the US, Canada and Mexico as Recognized by the AVN/MRF Model. The contour interval is 100 meters (from the Technical Procedures Bulletin, 1991).

Mean orography terrain elevations are lower than in the Nested Grid Model (NGM) terrain (600 to 1,000 meters lower over the Rockies, for example) but it represents reality better than the rolling hills of the AFGWC GSM terrain. In mean orography, elevation in the tropics is *higher* than that of the NGM. The NMC GSM also includes the effects of gravity wave drag, a sea-surface temperature analysis (the AFGWC GSM uses *climatological* sea-surface temperatures), dynamically interactive clouds, and a marine stratus parameterization.

8.2 The Medium Range Run (MRF).

The MRF is run at 0000Z only. It provides a medium-range global forecast out to 10 days. Twice a month, it is run out to 15 days on an experimental basis. The 0000Z run time was chosen to maximize the amount of rawinsonde data available to the model. The models used for analysis and forecasting are the same as the AVN run. It takes 2 hours and 55 minutes to run the entire analysis and forecast out to 10 days on the CRAY. If it fails on the CRAY after the 144-hour point, no backup is attempted.

If the CRAY is down for a prolonged period, the UK and AFGWC GSM models are used as back-up.

As with the AVN, MRF uses SSI to perform its analysis. A very late data cut-off time (H+6 hours) is used to collect as much global data as possible. The MRF initialization should be slightly better than the AVN's due to the increase in the amount of data available. Additionally, late arriving data from locations such as Asia affects the forecast for the U.S. because of the nature of spectral representation.

8.3 The Early Run (ERL). The ERL is run on a 12-hour cycle. It provides a quick-look regional forecast update using an early data cut-off, but 6- and 12-hourly data continues to come in long after the observation time. The data cut-off is the time observations must be received in order to be used in a particular run. The data cut-off time for the ERL is H+1:15.

8.3.1 The ERL Analysis. The analysis portion of the ERL run is based on a method known as "successive correction," a highly modified version of the original Cressman analysis method of 1959. It is *not* an OI anaysis method. It is produced by making corrections to the 6-hour forecast fields (First-Guess) generated in the previous run's final run, which will be described later. The corrections are interpolated onto a regularly spaced grid and added to the First-Guess fields to produce the analysis, which does not use data from one level to modify data at another, as an OI analysis would. Corrections are applied to the 10 standard constant-pressure levels through 100 mb on a 129 x 129 point, 190.5-km mesh (equal to the AFGWC half-mesh) PST grid.

8.3.2 The 48-hour Limited Fine Mesh (LFM). The LFM is the forecast model for the ERL. It makes its forecast on seven sigma levels: a boundary level, three tropospheric levels, and three stratospheric levels. The forecast is run out to 48 hours and is the back-up model for the NGM. There is no back-up model for the LFM, which is scheduled to be turned off in the near future.

When the LFM run is complete, jobs are executed to generate graphic and alphanumeric bulletins and further manipulate the forecast. An example of the output is the Model Output Statistics (MOS) forecast, which takes forecast elements directly from the LFM outputs and uses them as prediction variables in previously derived regression equations to predict an assortment of weather elements not directly forecast by any dynamic prediction model. Examples include:

- Probability of precipitation.
- Maximum and minimum temperatures.
- Indicators of severe weather.

8.4 The Regional Run (RGL). RGL is run on a 12-hour cycle with a data cut-off time of H+2 hours. It provides more detailed regional forecasts by using full rawinsonde data and more detailed precipitation guidance. The RGL analysis and forecast are executed on the CRAY; they each take 15 minutes to run. The NAS9000 is too slow to run the RGL. When the CRAY is down, the LFM is used as a back-up.

8.4.1 Regional Optimum Interpolation (ROI). The ROI is used for the RGL prognosis (the Nested Grid Model--NGM). It is similar to the AFGWC HIRAS analysis in its use of optimum interpolation. ROI differs from the HIRAS in two ways: It does not undergo a spectral transformation (the ROI is strictly a gridpoint analysis) and it has a different run frequency than HIRAS. ROI is run five times in a 12-hour cycle called the "Regional

Data Assimilation System," or "RDAS." The upper-air HIRAS analysis is only run twice in the 6-hour AWAPS cycle. An explanation of the RDAS cycle (T-12 to T-00) follows. The "T-" numbers represent data cut-off times minus the number of hours indicated and give the time the analyses are performed. Analyses between T-12 and T-00 are considered "one-way." This means that data from outside the boundary area can affect the analysis within the C-grid, but not vice versa. Figure 23 shows that portion of the Northern Hemisphere covered by the C-grid.

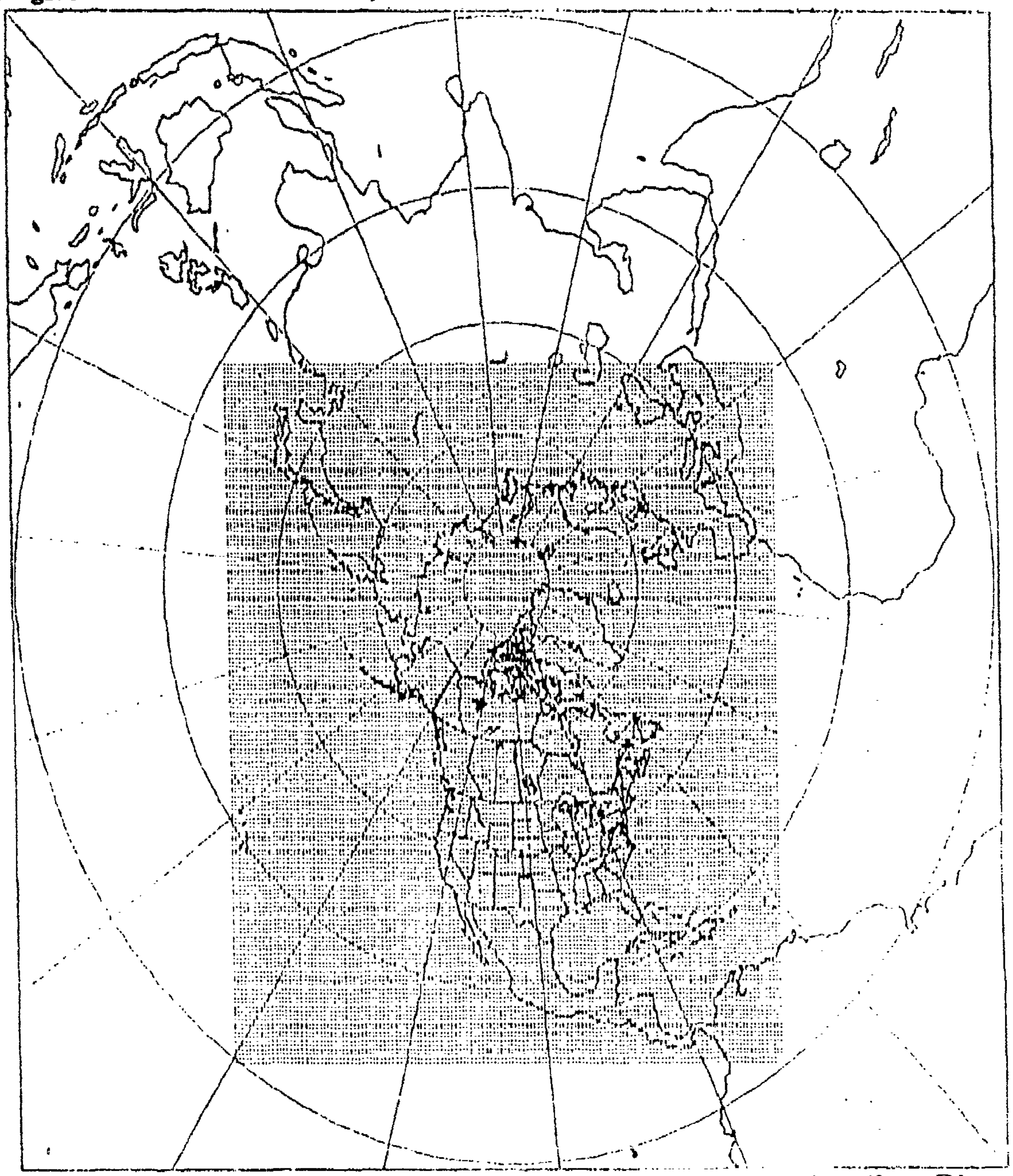

Figure 23. The NGM "Super-C" Grid. The grid area is 147 by 161 points (from Dimego et al., 1992).

T-12 The first analysis is performed using conventional data along with the output analysis from the Global Data Assimilation System (GDAS) for the background fields; this is the same way in which the AFGWC First-Guess is used in the HIRAS analysis. Since the prognosis and subsequent analyses in this cycle are primarily regional, rather than hemispheric, initializing the boundary areas of the regional analyses by using the analysis from GDAS is necessary to ensure that the longest wave components (which extend beyond the regional grid) are accurate. When the ROI analysis is complete, the NGM runs a 3-hour forecast on the C-grid for use as part of the background in the next analysis. This 3-hour forecast acts as a First-Guess for the next analysis. The C-grid is a regional grid covering only a portion of the Northern Hemisphere.

T-9 The second analysis is performed with the latest conventional data, the 3-hour NGM C-grid fields, and GDAS data. The data from GDAS is interpolated from the GDAS analysis valid at T-12 and T-6. This interpolated set of fields is used as boundary data for the analysis; it only covers the part of the hemisphere that the NGM C-grid data does not cover. The NGM and GDAS data is used as the background for the analysis.

T-6 The third analysis is performed with the latest conventional data, the latest 3-hour NGM C-grid fields, and GDAS data. The data from GDAS is the GDAS analysis valid at this time. The GDAS analysis is again only used to provide boundary conditions outside the C-grid of the NGM. The NGM and GDAS data are used as the background for the analysis. When the analysis is complete, the NGM performs another 3-hour forecast.

T-3 The fourth analysis is performed with the latest conventional data, the 3-hour NGM C-grid fields, and GDAS data. The data from GDAS is interpolated from the GDAS analysis valid at T-6 and a 6-hour forecast (valid at T-00) produced by the AVN. This interpolated set of fields is used as boundary data for the analysis; it only covers the part of the hemisphere that the NGM C-grid data does not. The NGM and GDAS data are used as the background data for the analysis. When the analysis is complete, the NGM performs another 3-hour forecast.

T-00 The final ROI analysis is accomplished by using the latest conventional data, the last NGM 3-hour forecast, and the latest analysis data from the GDAS to cover the boundary areas. To account for any differences between the NGM 3-hour forecast and the surrounding GDAS analysis, an area around (and ten gridpoints into) the C-grid is used as a buffer. Within this area, the data between the NGM forecast and the GDAS analysis is interpolated to connect the two data sets smoothly. When completed, this analysis is used to initialize the run of the NGM's 48-hour forecast.

8.4.2 The Nested Grid Model (NGM) is the prognosis model used by the RGL. The grid space for the analysis is about 1.5° latitude x 2.0° longitude over North America, and about 3° elsewhere. The analysis data fields are interpolated to the NGM grids and subjected to a normal mode initialization that brings the mass and motion fields back into approximate balance. The vertical resolution for the NGM is the same as that shown in Figure 21. The forecast, which at one time used a nested set of three computational grids referred to as "A", "B," and "C," now uses only two; the A-grid is no longer used. The B-grid, with its current resolution, has been expanded horizontally to cover the entire Northern Hemisphere. The C-grid has been expanded to cover an area a little larger than the original B-grid.

Figure 24 shows the grids and their areal coverage. The new B-grid provides boundary data for the interior C-grid, which has the finest horizontal resolution of the two.

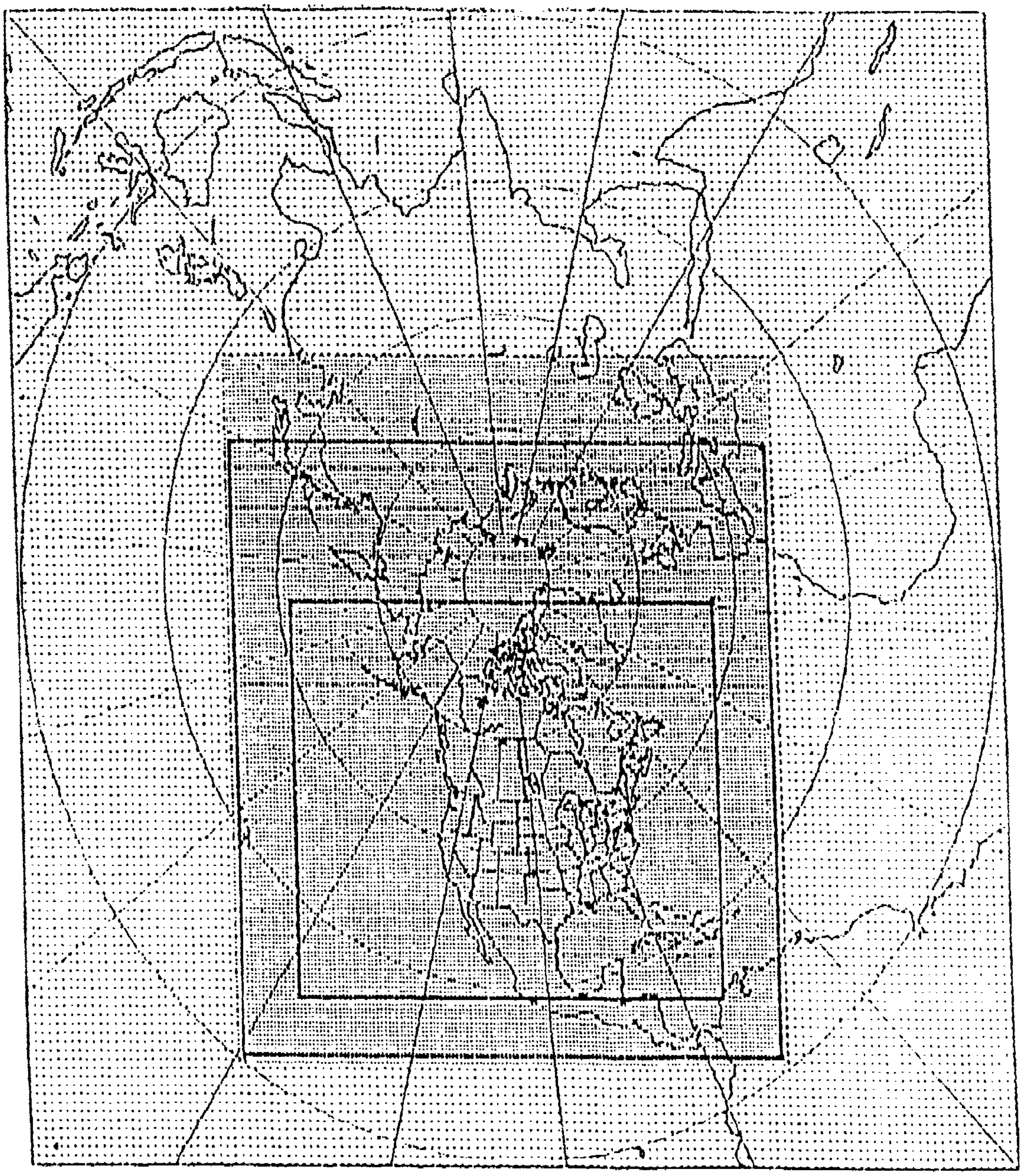

Figure 24. The NGM "Super-C" Grid Overlaying the NGM B-Grid. The boxes within the C-grid outline the areal coverage of the original Band C-grids of the NGM prior to the deletion of the A-grid (from Dimego et al., 1991).

The NGM forecasts out to 48 hours, but a few elements (such as temperature) are extrapolated beyond the end of the forecast period. The NGM forecasts some elements (such as vertical velocities and precipitation) on the C-grid. Those elements that do not need such a high resolution (500-mb heights, thickness, surface isobars, and 700-mb moisture/heights) are interpolated out to the B-grid.

The terrain used is a mean orography with greater peaks and valleys than the domes of the AFGWC GSM and the NMC Spectral Model (see Figure 25). Like the LFM, a full range of MOS data is available based on the NGM forecast. Since MOS data makes corrections for a model's biases based on its historical performance, any significant change to the model intended to decrease the effects of a specific bias also decreases the accuracy and reliability of the MOS. This also applies to the LFM.

8.5 The Final Run (FNL). This run produces the best possible First-Guess to be used as a foundation for the GDAS in the subsequent analysis cycle. It is run every 6 hours. The final run is executed as a paired analysis/6-hour forecast like the AFGWC First-Guess. One difference is that the 6-hour forecast is the basis for three different analysis schemes at NMC versus just one (HIRAS) at AFGWC. The analysis and forecast systems used are identical to the AVN/MRF runs, which have better resolution than the AFGWC First-Guess. The final run takes 20 minutes on the CRAY. If the CRAY fails, the back-up is the earlier AVN run's 12-hour forecast. There is no attempt to perform intermediate (0600/1800Z) updates.

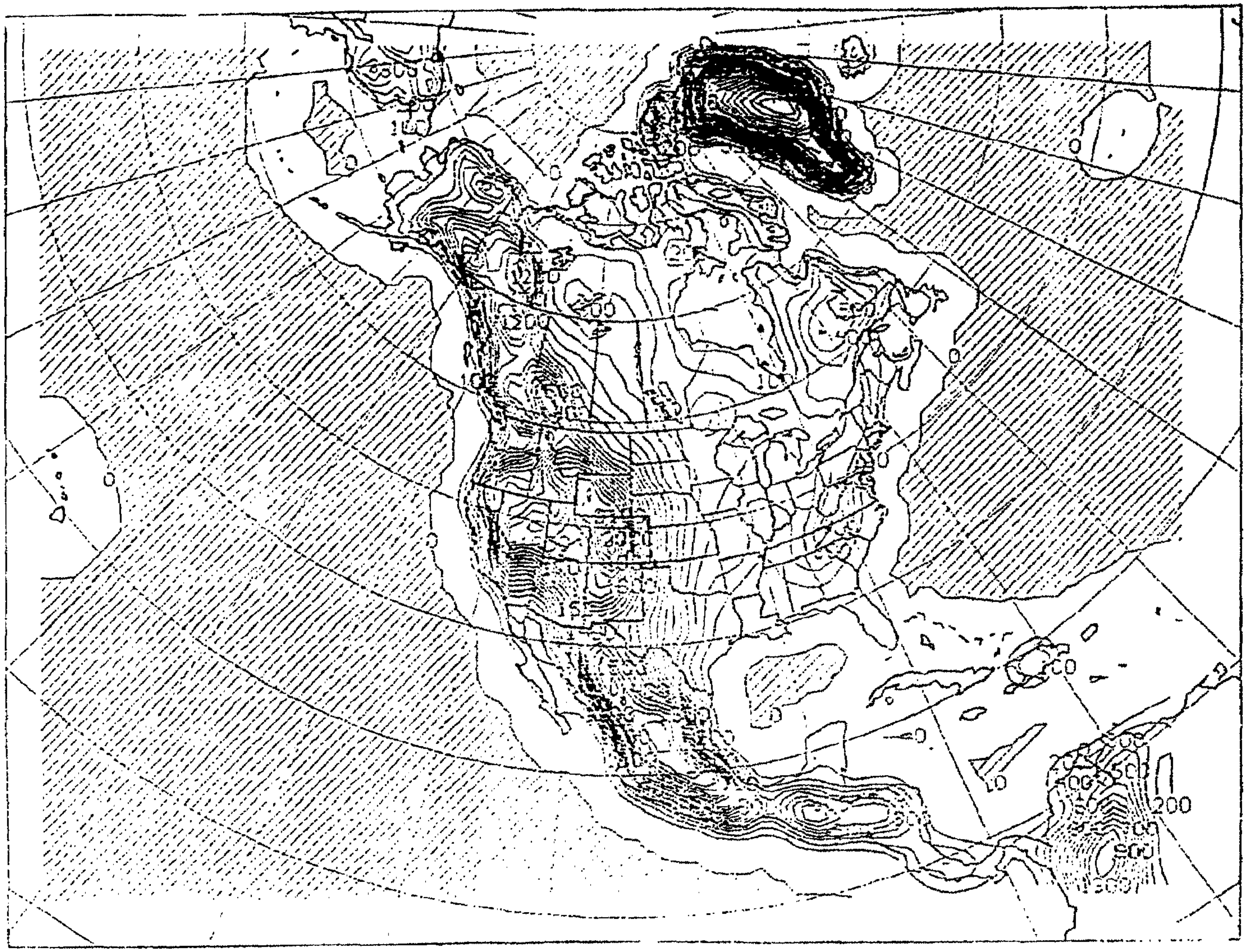

Figure 25. The C-Grid Topography of the NGM. The elevation of recognized land surface is contoured in 100-meter intervals (from Petersen et al., 1991).

Chapter 9

STRENGTHS AND WEAKNESSES OF THE NMC MODELS

***Note:** The most important thing to remember when considering the inherent deficiencies in each of the models is that one problem can cause many others. For example, a cold bias in a particular area usually causes heights to be too low. This could result, for just one example, in the jet being placed too far south.*

9.1 Limited Fine Mesh (LFM). The LFM has been operational longer than any of the other models discussed here. As a result, information on the LFM's characteristics are more accurate and complete than for any of the other models. LFM weaknesses include the following:

- The LFM is too cold over the Rockies.

- The LFM has problems forecasting systems moving out of the Rockies. It often lowers 500-mb heights and mean sea-level pressures too quickly east of the Rockies, resulting in the mispositioning of low-level southerly jets. Moisture with these jets and associated surface fronts are moved too quickly eastward across the plains and the Mississippi valley. The heaviest precipitation, therefore, is observed south and west of the forecast location.

- The LFM forecasts too many cyclones downstream from major mountain barriers. Arkansas and Oklahoma are particularly vulnerable to spurious cyclogenesis.

- The LFM moves cyclones too slowly in the fall and too quickly in the spring.

- The LFM underforecasts the strength of cyclones over ocean areas.

- The LFM rarely forecasts cyclogenesis adequately over Nevada when an upper-air trough digs towards Nevada and moves east of 126° W with an upper-level jet crossing the Sierra Nevada range between 30 & 40 °N.

- The LFM is weak in forecasting explosive cyclogenesis in the western North Atlantic. During maximum deepening, the LFM was found to lag behind by 10 mb for the first 36-48 hours. For all time ranges, there is an eastward movement bias for these systems. While the 12-hour forecast generally moves cyclones too far east-southeast, the rest of the prognosis forecasts them too far northeast. This also causes cyclones to move too fast, with a mean distance error of 341 km.

- Anticyclones on the 48-hour forecasts are not strong enough (especially east of 100° W) and are forecast too far southeast. The error is greatest in the eastern U.S. and on the east coast, but it also occurs in other sections of the U.S. and off both coasts. The mean distance error is 510 km. Because of the return flow from these anticyclones, advection of moisture and warm air develop too quickly. This affects precipitation forecasts.

- The LFM has difficulty forecasting Arctic air masses. Sometimes, when in reality only a low-pressure trough forms, the sea-level pressure is lowered too much in the cold air, the 1,000-500 mb layer is warmed, and the surface low tracks too far northward into the cold air.

- The LFM has a tendency to overforecast precipitation in the cooler part of the year and underforecast it in the summer.

9.2 The Nested Grid Model (NGM).

- The NGM has a cold bias over the Rocky Mountains. The bias was partially corrected by implementing a hemispheric temperature adjustment (Phillips 1987). The adjustment lessened the effects of the cold bias over the Rocky Mountains, but created a warm bias over the Appalachians. The NGM is colder than the LFM over the Rockies.

- The NGM takes diurnal changes in temperature into account; the LFM does not.

- There is a diurnal problem in the NGM's ability to forecast maximum temperatures in that the surface maximum temperature lags behind the model's insolation maximum by several hours. If skies are clear during the day, the problem is more pronounced. As cloud cover increases, the problem becomes less significant because the model recognizes the decreasing effect of insolation with increased cloud cover.

- There is a pronounced diurnal problem with low-level wind forecasts in that forecasts in the lowest 35 mb (the midpoint is about 150 meters) peak at night, with a minimum at midday. In order to produce a more realistic forecast at anemometer level, the model needs higher vertical resolution and a more realistic method for modeling the downward transport of momentum during the day. Currently, the model reflects a wind more typical of a nocturnal jet.

- Due to its horizontal resolution (85 km), NGM tends to forecast sea breezes several hundred kilometers farther inland than they actually are. Due to the strong convergence forecast so far inland, the NGM also overforecasts the extent of sea-breeze enhanced precipitation in those areas. The effect also occurs around the Great Lakes. Unrealistic monsoonal-scale upslope flow and heavy precipitation are often predicted over Central America for the same reason.

- Snow and ice fields are included and updated weekly by the National Environmental Satellite Data and Information Service (NESDIS). These fields affect the albedo in the radiation calculations as well as the sensible and latent heat fluxes at the surface. For example, evaporation from a frozen surface is not allowed. Because the ice/snow fields used by the NGM have a coarse resolution, snow cover around the Great Lakes can be mistakenly interpreted as ice cover, making the lakes appear to be frozen. This makes the 35 gridpoints over the Great Lakes insignificant as moisture or heat sources. The ability of the model to forecast lake-effect events decreases as snow accumulates around the lakes in early winter.

- Since there is only one snow-cover analysis during the week (usually on Monday), significant changes in snow cover during the week will not be noted. Since the NGM cannot melt snow, the surface temperature cannot be above 0° C in an area of thin snow cover, even when there is strong insolation. The existence of snow cover in the model at a point where it should be snow-free has been shown to reduce the bottom-layer air temperature in some cases by over 6° C. When forecasting rain or snow, therefore, forecasters must consider the model's deficiencies. Note also that heights, especially in the mid-levels, could be forecast too low or too high depending on the snow cover, since the albedo or the effects of insolation may be the opposite of what's really happening.

- The NGM has a tendency to forecast the movement of surface cyclones too slowly. In a study by Grumm and Siebers (1989), the largest positional errors were found in the southeast quadrant of the NGM. Forecast positions were found to be northwest of the analyzed position. The mean distance errors grew from 90 km at the 24-hour point to 310 km at the 48-hour point. The second largest error was found in the southwest quadrant. Cyclones were too far north of the analyzed position. The error increased from about 160 km at the 24-hour point to 200 km at the 48-hour point. No bias was determined in the northern quadrants, because the forecast versus analyzed positions were too scattered.

• Grumm and Siebers determined that the NGM underdevelops lows in the Atlantic off the New England coast; this is especially true of "bombs" that begin development near Cape Hatteras. However, NGM low predictions are too deep over the North American continent at all times. A checklist was developed to forecast "bombs" off the east coast. In most cases a vorticity maximum moves over the already strong thermal gradient between the Labrador current and the Gulf stream. Cyclogenesis occurs, forming a new low or deepening an already existing one. The low then deepens dramatically as it moves N and NE. The checklist developed by Sanders and Auciello (1989) applies only to the Atlantic north of 40° N and west of 60° W. The checklist predicted 20 "bombs" between October 1988 and March 1989 and correctly forecast 13 of the 16 that occurred. At least four of the following six criteria must be met:

1. The strength of the 500-mb absolute vorticity maximum is equal to or greater than $1.7 \times 10^{-4}\ s^{-1}$.

2. The vorticity maximum stays the same or strengthens during the NGM forecast.

3. The vorticity maximum is forecast to move faster than 30 knots.

4. The vorticity maximum crosses the Atlantic coast between 32 and 45° N.

5. There is a jet max greater than 100 knots at 250 mb or 300 mb, just south of the initial vorticity maximum.

6. The NGM forecasts a surface low of 990 mb or deeper over the Atlantic Ocean north of 38° and west of 55°

• The NGM often over-deepens lows coming out of the Rocky Mountains.

• Another study by Grumm and Siebers (for the period November 1988-January 1989) found that anticyclones were incorrectly positioned by 261 km and 334 km at the 24- and 36-hour points, respectively. The latter, however, is much better than the LFM's 510 km error. The NGM also slightly over-forecasts pressure centers in the Rockies and under-forecasts them in the eastern U.S., probably due to the cold and warm biases, respectively.

• NGM precipitation forecast amounts are superior to the LFM and NMC GSM model when the associated 500-mb trough is positively tilted.

• The NGM has a problem forecasting heavy amounts of precipitation (greater than .5 inch/day) in the southern U.S. during the cool season. A study by N. W. Junker (for the winters of 1987-88 and 1988-89) showed the greatest number of forecasting misses to be along the Gulf coast, but decreasing northward.

• The NGM over-forecasts light precipitation in the summer.

9.3 The NMC GSM Model. Most of the error discussions that follow should be interpreted with caution; they are averaged over a limited period of time and may depend on the flow regime. Also, the GSM was recently upgraded from an 80- to a 126-wave model.

- The 80-wave GSM had a general cold bias that was greatly reduced by the new 126-wave model, which appears to have a slight cold bias in the mid-latitudes.

- The new 126-wave model appears to handle coastal and lee-side cyclogenesis better than the 80-wave version and better than the NGM and LFM models.

- The GSM model has an upper-level easterly bias over the tropics.

- In summer, heights are over-forecast over land and under-forecast over oceans. These errors have been linked to apparent thermal forcing.

- The GSM under-forecasts the intensity of Arctic highs in central and western Canada.

- The GSM makes the plunge of Arctic air into the U.S. too slow.

9.4 The Spectral Statistical Interpolation Analysis System. Due to the relative newness of this model, information on its performance is limited. Testing, which concentrated on the system's effects on forecast models, showed slight overall improvement in forecast skill up to day 5 when compared to a parallel forecast initialized by the old OI analysis. Beyond day 5, no discernible differences were noted.

GLOSSARY

AFGWC	Air Force Global Weather Central
ASDAR	Aircraft to Satellite Data Relay, a system in which wide-bodied aircraft are fitted with equipment to obtain meteorological data.
AVN	Aviation run, National Weather Service
AWAPS	Advanced Weather Analysis and Prediction System, Air Force Global Weather Central
AWSPE	Air Weather Service Primitive Equation, the forecast model used at Air Force Global Weather Central prior to acquisition of the Global Spectral Model by the Air Force
CPS	Condensation Pressure Spread
CPU	Computer or Central Processing Unit
DMSP	Defense Meteorological Satellite Program
ERL	Early Run, National Weather Service
FNL	Final Run, National Weather Service
GADB	Global Applications Database, Air Force Global Weather Central
GDAS	Global Data Assimilation System - National Weather Service
GOI	Global Optimum Interpolation, National Weather Service
GSM	Global Spectral Model, Air Force Global Weather Central and National Weather Service
HIRAS	High Resolution Analysis System, Air Force Global Weather Central
LFM	Limited Fine Mesh, National Weather Service
MRF	Medium Range Forecast run, National Weather Service
NGM	Nested Grid Model, National Weather Service
NESDIS	National Environmental Satellite, Data, and Information Service
NMI	Normal Mode Initialization

NWS	National Weather Service
OI	Optimum Interpolation
PST	Polar-stereograghic
QC	Quality Control
RAOB	Radiosonde/Rawinsonde Observation
RDAS	Regional Data Assimilation System, National Weather Service
RGL	Regional Run, National Weather Service
ROI	Regional Optimum Interpolation, National Weather Service
RTNEPH	Real-Time Nephanalysis model, Air Force Global Weather Central
RWM	Relocatable Window Model, Air Force Global Weather Central
SDHS	Satellite Data Handling System, Air Force Global Weather Central
SGDB	Satellite Global Database, Air Force Global Weather Central
SNODEP	Snow Depth model, Air Force Global Weather Central
SSI	Spectral Statistical Interpolation, National Weather Service
SSM/I	Special Sensor Microwave/Imager, a Defense Meteorological Satellite Program sensor
5LAYER	The primary cloud forecast model used at Air Force Global Weather Central

APPENDIX A

AFGWC SATELLITE DATA HANDLING SYSTEM (SDHS) PRODUCTS

AFGWC-produced SDHS facsimile products are listed below, along with the models used to support them.

Facsimile Chart	Numeric Model
1. ASNH	First-Guess, HIRAS, 5LAYER.
2. FSNH2	AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
3. FSNH3	AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
4. FUNH2	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
5. FUNH3	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
6. FHNH2	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
7. FHNH3	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
8. FANH25	LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
9. FANH3	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
10. WWUS12	AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
11. WWUS A-C	AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
12. FANA	5LAYER, AFGWC GSM, supplemented with NMC GSM (AVN RUN) and NGM.
13. FENH66-69	NMC GSM (MRF RUN)
14. FENH1A	NMC GSM (MRF RUN)
15. FATR	AFGWC GSM
16. FAME	AFGWC GSM

APPENDIX B

AFGWC COMPUTER-GENERATED PRODUCTS

Facsimile Chart	Numeric Model	Facsimile Chart	Numeric Model
1. AXASA-D KGWC	HIRAS	12. FUEU KGWC	AFGWC GSM
2. AXIO(i) KGWC	HIRAS	13. FUNH(ii) KGWC	AFGWC GSM
3. AXPW KGWC	HIRAS	14. FUNT(ii) KGWC	AFGWC GSM
4. FAEH KGWC	AFGWC GSM	15. FUPA(ii) KGWC	AFGWC GSM
5. FAEH18 KGWC	AFGWC GSM	16. FUTR(ii) KGWC	AFGWC GSM
6. FAWH KGWC	AFGWC GSM	17. FUWH(ii) KGWC	AFGWC GSM
7. FEAS50 KGWC	AFGWC GSM	18. FUXP(ii) KGWC	AFGWC GSM
8. FEEU KGWC	AFGWC GSM	19. FXAS(i) KGWC	AFGWC GSM
9. FENH KGWC	AFGWC GSM	20. FXEU(i) KGWC	AFGWC GSM
10. FSNT KGWC	AFGWC GSM	21. FXIO(i) KGWC	AFGWC GSM
11. FUCA KGWC	AFGWC GSM	22. FXPW(i) KGWC	AFGWC GSM

APPENDIX C

NMC COMPUTER-GENERATED PRODUCTS

NMC-produced facsimile products are listed below, along with the models used to support them.

Facsimile Chart	Numeric Model
1. ANAL 500 mb WITH PLOT DATA	ERL ANAL
2. ANAL 700 mb WITH PLOT DATA	ERL ANAL
3. ANAL 850 mb WITH PLOT DATA	ERL ANAL
4. OBS WND ALOFT 4-PANEL	LFM
5. ANAL 700 mb HGT/MEAN RH SFC-aprox 450 mb	ROI ANAL
6. ANAL 850 mb HGT/ISOTHERM	ROI ANAL
7. ANAL 500 mb HGT/REL VORT	ROI ANAL
8. ANAL MEAN SLP/1000-500 THKNS	ROI ANAL
9. ANAL 200 mb TROPIC WITH DATA	ERL ANAL
10. COMPOSITE MOISTURE CHART/FREEZING LVL	ROI ANAL
11. COMPOSITE MOISTURE CHART/SFC-500 mb MEAN RH	ROI ANAL
12. COMPOSITE MOISTURE CHART/LIFTED AND K INDICES	ROI ANAL
13. COMPOSITE MOISTURE CHART/SFC-500 PRECIPITABLE WATER	ROI ANAL
14. ANAL 300 mb WITH DATA	ERL ANAL
15. ANAL SFC/1000-500 mb THKNS	SSI ANAL
16. ANAL 500 mb	SSI ANAL
17. ANAL 500 mb MERCATOR PROJECTION	SSI ANAL
18. ANAL 700 mb MERCATOR PROJECTION	SSI ANAL
19. PROG 36 hr 300 mb HGT/WND	NMC GSM (AVN RUN)

20.	PROG 36 hr 700 mb HGT/WND	NMC GSM (AVN RUN)
21.	PROG 36 hr 700 mb HGT/WND	NMC GSM (AVN RUN)
22.	PROG 36 hr 500 mb HGT/WND	NMC GSM (AVN RUN)
23.	PROG 12 hr WND ALOFT 8 PANEL	LFM
24.	PROG 12 hr 700 mb HGT/MEAN RH SFC-aprox 450 mb	NGM
25.	PROG 12 hr 850 mb HGT/ISOTHERM	NGM
26.	PROG 12 hr 500 mb HGT/REL VORT	NGM
27.	PROG 12 hr MEAN SLP/1000-500 THKNS	NGM
28.	PROG 24 hr 700 mb HGT/MEAN RH SFC-aprox 450 mb	NGM
29.	PROG 24 hr 850 mb HGT/ISOTHERM	NGM
30.	PROG 24 hr 500 mb HGT/REL VORT	NGM
31.	PROG 24 hr MEAN SLP/1000-500 THKNS	NGM
32.	PROG 36 hr 700 mb HGT/MEAN RH SFC-aprox 450 mb	NGM
33.	PROG 36 hr 850 mb HGT/ISOTHERM	NGM
34.	PROG 36 hr 500 mb HGT/REL VORT	NGM
35.	PROG 36 hr MEAN SLP/1000-500 THKNS	NGM
36.	PROG 48 hr 700 mb HGT/MEAN RH SFC-aprox 450 mb	NGM
37.	PROG 48 hr 850 mb HGT/ISOTHERM	NGM
38.	PROG 48 hr 500 mb HGT/REL VORT	NGM
39.	PROG 48 hr MEAN SLP/1000-500 THKNS	NGM
40.	PROG 48 hr 500 mb HGT/WND	NMC GSM (AVN RUN)
41.	PROG 36 hr 500 mb HGT/WND	NMC GSM (AVN RUN)
42.	PROG 2-PANEL 24 & 36 hr SFC/THKNS	NMC GSM (AVN RUN)
43.	PROG 4-PANEL ANAL, 12, 24 & 36 hr (BAROCLINIC)	NMC GSM (AVN RUN)

44.	PROG 36 hr SFC/THKNS	NMC GSM (AVN RUN)
45.	PROG 24 hr SFC/THKNS	NMC GSM (AVN RUN)
46.	PROG 4-PANEL PRECIP PROBABILITY	LFM
47.	PROG 36 hr 700 mb	NMC GSM (AVN RUN)
48.	PROG 48 hr 1000 mb MERCATOR PROJECTION	NMC GSM (AVN RUN)
49.	PROG 36 hr 700 mb MERCATOR PROJECTION	NMC GSM (AVN RUN)
50.	PROG 36 hr BOUNDARY LAYER WINDS/RH	NMC GSM (AVN RUN)
51.	PROG 4-PANEL 24,36,48 & 60 hr MAX/MIN TEMPS	NGM
52.	PROG 84 hr 500 mb HGTS	NMC GSM (MRF RUN)

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81 TFW/WE, Unit 5975, APO AE 09497-5000 1
20OSS/DOM, Unit 5475, APO AE 09466-5000 1
10 TFW/DOM, Unit 5685, APO AE 09470-5000 1
32OSS/WE, Unit 6795, APO AE 09719-5000 1
86WF, Unit 3090, APO AE 09094-5000 1
40 SW/WX, Unit 6160, APO AE 09601-5000 1
52 OSS/WEF, Unit 3720, Box 195, APO AE 09126-5000 1
16AF/SWO, Unit 6365, APO AE 09641-5000 1
401 CSG/WE, Unit 6490, APO AE 09641-5000 1
39 TACG/DOM, Unit 7090, Box 115, APO AE 09824-5000 1
52TFW/OTM, APO AE 09705-5000 1
OL-C, 7WS, CMR445, Box 260, APO AE 09046-5000 1
48 Weather Flight, APO AE 09464-5000 1
105 Weather Flight, Tennessee Air National Guard, PO Box 17267,
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107 Weather Flight, Selfridge ANGB, MI 48045-5024 1
110 Weather Flight, MO ANG, 131TFW, Bridgeton, MO 63044-2371 1
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113 Weather Flight, Hulman Fld, Terre Haute, IN 47830-5000 1
116 Weather Flight, WA ANG, Bldg 304, McChord AFB, WA 98433-5000 .. 1
120 Weather Flight, Buckley ANGB, CO 80011-9599 1
121 Weather Flight, Stop 28, Andrews AFB, MD 20331-6539 1
122 Weather Flight, New Orleans NAS, LA 70143-0200 1
123 Weather Flight, Portland IAP, OR 97218-2797 1
125 Weather Flight, PO Box 580340, Tulsa AFS, OK 74158-0340 1
126 Weather Flight, WIANG, 350 E College, Milwaukee, WI 53207-6298 ... 1
127 Weather Flight, Forbes Fld, Topeak, KS 66619-5000 1
130 Weather Flight, Yeager Apt, Charleston, WV 25311-5000 1
131 Weather Flight, Barnes Map, Westfield, MA 01085-1385 1
140 Weather Flight, Willow Grove NAS, PA 19090-5105 1
146 Weather Flight, GTR Pittsburg ANG AN, PA 15231-0459 1
154 Weather Flight, Camp Robinson, North Little Rock, AR 72118-2200 .. 1
156 Weather Flight, 5225 Morris Fld Dr., Charlotte, NC 28208-5797 1
159 Weather Flight, c/o HQ FLANG, State Arsenal, St Augustine,
FL 32085-1008 1
164 Weather Flight, Rickenbacker ANGB, OH 43217-5007 1
165 Weather Flight, Standiford Fld, Louisville, KY 40213-2678 1
181 Weather Flight, 8150 W Jefferson Blv, Dallas, TX 75211-9570 1
195 Weather Flight, 4146 Naval Air Rd., Port Hueneme, CA 93041-4001 ... 1
199 Weather Flight, Wheeler AFB, HI 96854-5000 1
200 Weather Flight, 5680 Beulah Rd., Sandston, VA 23150-6109 1
202 Weather Flight, Otis ANGB, MA 02542-5028 1
203 Weather Flight, Ft Indiantown GAP, Annville, PA 17003-5002 1
204 Weather Flight, McGuire AFB, NJ 08641-6004 1
207 Weather Flight, 3556 N. Michigan Rd., Shelbyville, IN 46176-4914 ... 1
208 Weather Flight, 206 Airport DE, St Paul, MN 55107-4098 1
209 Weather Flight, PO Box 5218, Austin, TX 78763-5218 1
210 Weather Flight, Ontario ANGB, CA 91761-7627 1
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